SEE FOLLOWING NOTE

VOIR NOTE CI-APRÈS

PARTS OF THE ORIGINAL DOCUMENT ARE OF POOR REPRODUCTIVE QUALITY.

MICROMEDIA LIMITED HAS ATTEMPTED TO PRODUCE THE BEST POSSIBLE COPY.

CERTAINES PARTIES DU DOCUMENT ORIGINAL SONT DE PIÈTRE QUALITÈ DE REPRODUCTION.

MICROMEDIA LTEE A ESSAYEE DE PROCURER LE MEILLEUR EXEMPLAIRE POSSIBLE.

CANADIAN CLIMATE CENTRE

REPORT NO. 89-5

OVER-WATER GUST FACTORS

by

R.D. Brown
and
V.R. Swail

ATMOSPHERIC ENVIRONMENT SERVICE

DOWNSVIEW, ONTARIO

1989

THIS REPORT HAS RECEIVED ONLY LIMITED CIRCULATION BECAUSE OF THE SPECIAL NATURE OF THE PROJECT. HOWEVER, REFERENCE IS PERMITTED IF THE WORDS "UNPUBLISHED MANUSCRIPT" ARE MADE PART OF THE BIBLIOGRAPHIC ENTRY, IN ACCORDANCE WITH ACCEPTED PRACTICE.

OTHER CANADIAN CLIMATE CENTRE (CCC)
SCIENTIFIC SERIES INCLUDE:

1.	CS series	- CCC Climatological Study
2.	CLI series	- CCC Climatological Memoranda
3.	CDS/DS series	- CCC Climatic Data Summary
		- CCC Documentation Sheet

For further information on climatological publications contact the

Climatological Services Division
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario M3H 5T4

93-00281/

OVER-WATER GUST FACTORS

by

R.D. Brown
and
V.R. Swail

Hydrometeorology and Marine Division
Canadian Climate Centre

This work was supported by the Federal Panel on Energy R & D

A publication of the Canadian Climate Program

Abstract

This report examined the characteristics of over-water gust factors and turbulence at three offshore locations, and evaluated a number of techniques for predicting over-water gusts. Mean gust factors were found to agree well with values previously published by DnV (1977) and Smith and Chandler (1987). Typical values for maximum 1 and 3 sec gusts in one hour were found to be 1.34 and 1.30 respectively. Gust factors were found to be most sensitive to variation in gust duration (t), elevation and record length (T). Wave height, wind speed, and atmospheric stability were observed to have only slight influences on gust factors.

Mean values for σ/u_* of 2.26 and 2.58 were found at two offshore locations, in general agreement with published values. Corresponding mean values for σ/U were 0.080 and 0.106. σ/u_* was observed to display less sensitivity to wind speed and elevation than σ/U, which suggested it was a more stable 'constant' to use in gust factor models. The inclusion of stability effects in the calculation of u_* was observed to decrease the height dependence of σ/u_*. This was found to be important for reliable prediction of gust factors from models which assume σ/u_* is constant in the boundary layer.

The gust factor model evaluation revealed that while several could provide good predictions of **average** gust factors, none were able to account for the observed variation in individual over-water gust factors. Incorporation of the Geernaert et al. (1987) drag coefficient/wave age relationship into existing gust models did little to improve results. A comparison of wave age with Forristall's (1987) wave factor revealed the two were linearly related at the BOW DRILL 3 site. This suggested σ/u_* was a simple linear function of wave age based on results presented in Forristall (1987). However, there was no evidence of this relationship in Geernaert et al.'s (1987) data from the North Sea. Further work and better data are required to develop a modelling technique which can replicate the observed variation in over-water gusts.

Résumé

Ce rapport examine les caractéristiques des facteurs de rafales et de la turbulence au-dessus de l'eau à trois emplacements du large des côtes. Il évalue plusieurs techniques de prévision des rafales qui surviennent au-dessus de l'eau. On constate que les facteurs moyens de rafales correspondent bien avec les valeurs déjà publiées par DnV (1977) et Smith and Chandler (1987). On établit que la valeur type, en une heure, est de 1,34 pour une rafale d'un maximum de 1 seconde et de 1,30 pour une rafale d'un maximum de 3 secondes. On trouve que les facteurs de rafales sont très sensibles à la variation de la durée de la rafale (t), à l'altitude et à la durée record (T). La hauteur des vagues, la vitesse du vent et la stabilité atmosphérique n'exercent qu'une faible influence sur les facteurs de rafales.

Pour σ/u_*, on a établi que les valeurs moyennes de 2,26 et de 2,58, à deux emplacements du large des côtes, correspondaient généralement aux valeurs publiées. Les valeurs moyennes correspondantes de σ/U étaient de 0,080 et de 0,106. On a constaté que σ/u_* est moins sensible à la vitesse du vent et à l'altitude que σ/U, fait donnant à penser qu'il s'agit d'une "constante" plus stable pour les modèles des facteurs de rafales. On s'est aperçu que l'inclusion des effets de stabilité dans le calcul de u_* atténuait la dépendance de σ/u_* par rapport à la hauteur. On a établi l'importance de ce fait pour la prévision fiable des facteurs de rafales à partir des modèles qui supposent que σ/u_* est constant dans la couche limite.

En évaluant les modèles des facteurs de rafales, on a montré que si plusieurs d'entre eux pouvaient donner de bonnes prévisions des facteurs moyens de rafales, aucun ne pouvait rendre compte de la variation observée dans les facteurs individuels de rafales au-dessus de l'eau. L'incorporation du rapport coefficient de frottement/âge de la vague de Geernaert et de ses collaborateurs (1987) n'a guère contribué à améliorer les résultats. En comparant l'âge de la vague avec le facteur de vague de Forristall (1987), on a constaté que ces deux éléments étaient liés par une relation linéaire à l'emplacement BOW DRILL 3. Ce σ/u_* ainsi suggéré est une fonction linéaire simple de l'âge de la vague, d'après les résultats présentés dans le document de Forristall (1987). Toutefois, rien n'a permis de faire apparaitre ce rapport dans les données de Geernaert et de ses collaborateurs (1987), données provenant de la mer du Nord. Il faut un complément de travail et de meilleures données pour concevoir une technique de modélisation qui puisse reproduire la variation observée dans les rafales survenant au-dessus de l'eau.

TABLE OF CONTENTS:

	Page
Abstract	i
Résumé	ii
Table of Contents	iii
1. INTRODUCTION	1
2. OFFSHORE GUST THEORY	2
2.1 Universal offshore gust factor method of Forristall (1987)	3
2.2 Universal offshore gust factor method of McClintock et al. (1987)	5
3. DATA SETS	7
3.1 WEST SOLE Platform	7
3.2 Bedford Tower	9
3.3 BOW DRILL 3	9
4. DATA ANALYSIS	11
4.1 Gust factor analysis	11
4.2 Characteristics of over-water gust factors	11
4.2.1 General	11
4.2.2 Variation of G(t,T) with gust duration, t	14
4.2.3 Variation of G(t,T) with measuring interval, T	14
4.2.4 Variation in G(t,T) with elevation, z	14
4.2.5 Variation of G(t,T) with stability	17
4.2.6 Variation of G(t,T) with wind speed and wave height	19
4.3 Characteristics of turbulence intensity over water	23
4.3.1 Variation of r/u_* with wind speed	26
4.3.2 Variation of r/u_* with elevation	26
4.3.3 Variation of r/u_* with stability	26
5.0 EVALUATION OF OVER-WATER GUST PREDICTION METHODS	29
5.1 Mean gust factor comparison	31
5.2 Individual gust factor comparison	33
5.3 Recommendations for computing offshore gust factors	35
6.0 CONCLUSIONS	38
7.0 REFERENCES	43
APPENDIX A: Gust analysis summary tables	45
APPENDIX B: Wind profile comparison for Walmsley (1988) model	51

1.0 INTRODUCTION

Knowledge of over-water wind speed and turbulence profiles in the 10-100 m elevation range is important for the design of offshore structures, particularly compliant structures which have typical peak response frequencies in the order of 30 seconds to 2 minutes. However, as Dello Stritto et al. (1985) pointed out, there is considerable disagreement in the gust factors and wind profile power law exponents published in design guidelines for offshore structures. Dello Stritto et al. attributed these disparities to inadequate data sets, and to the lack of a consistent definition of gust factors. In response to these observations, the International Workshop on Offshore Winds and Icing (Agnew and Swail, 1985) stated as one of its recommendations that a better understanding of gusts was required for offshore areas through identification and analysis of existing data sets or collection of appropriate data, the adoption of a standard method for computing gusts, and the establishment of a gust climatology for ocean areas.

These objectives formed the basis of a study carried out by SEACONSULT Limited (McClintock et al., 1987) in 1986/87 where a number of over-water wind data sets were analyzed to develop a universal "rigorous method for gust factor calculation" over water. This study produced a technique for predicting over-water gusts based on two basic assumptions: (1) that turbulence intensity, σ/U, was more-or-less constant over the open ocean under high wind conditions; and (2), that gust factors were normally distributed. Further details of the McClintock et al. approach to modelling gust are given in Section 2.2.

The SEACONSULT study produced a number of specific recommendations concerning further work on over-water gusts. The main recommendations were:

- that additional data sets be analyzed to increase confidence in the universal value of σ/U, and to examine its dependence on wind speed, stability and elevation;

- that the analysis be expanded to gust factors other than 1 sec (the SEACONSULT study restricted itself to 1 sec gusts).

The acquisition of a comprehensive over-water wind data set from the WEST SOLE platform in the North Sea provided the opportunity to look at these recommendations in more detail, as well to answer a number of questions raised by the SEACONSULT study. The main objectives of the study were:

(1) to determine the empirical characteristics of over-water gust factors i.e. the effect of gust duration, record length, height, wind speed, significant wave height and atmospheric stability;

(2) to investigate the magnitude and variation of turbulence intensity over water;

(3) to evaluate the performance of techniques for estimating offshore gust factors.

A brief overview of the boundary layer theory pertaining to over-water gusts is provided in the next section, along with a discussion of two 'universal' techniques for estimating over-water gust factors i.e. McClintock et al. (1987) and Forristall (1987). The data sets used in the analysis are described in the Section 3.0, while the results of the gust factor analysis are presented in Section 4.0. An evaluation of gust factor models is carried out in Section 5.0.

2.0 OFFSHORE GUST THEORY

It is a matter of common experience that the wind near the surface is continuously disturbed by random fluctuations know colloquially as gusts. The wind blowing over the ocean may be regarded as composed of an average wind speed, U, proportional to the gradient wind at higher altitudes, with the superposition of random, three-dimensional fluctuations of atmospheric turbulence (u_1, u_2, u_3). Thus the wind speed for any time, u(t), can be represented by

$$u(t) = (U + u_1, u_2, u_3)\ (t) \qquad (1),$$

where U is the mean wind speed in the downwind direction, and u_1, u_2, and u_3 are wind speed fluctuations in the downwind, crosswind and vertical directions. These turbulent fluctuations are responsible for the average vertical transport of horizontal momentum, which is the mechanism by which the surface shear stress is transmitted through the atmospheric boundary layer. Thermal effects can enhance (unstable case) or retard (stable case) turbulent energy transfer. However, in moderate to strong winds, mechanically produced turbulence from surface roughness usually dominates, and atmospheric stability plays a minor role (Fordham, 1985).

Turbulence levels and associated spectral levels and gust factors depend on the wind speed and the aerodynamic roughness of the surface. The situation is complicated over water because surface roughness is a function of sea state, which in turn is dependent on a number of parameters including wind speed, fetch, water depth and the developmental stage of waves. There is, therefore, a complicated interrelationship between wind speed, sea state and turbulence. A brief overview of the basic theory involved in over-water turbulence is given below assuming a neutral boundary layer. This approximation will usually be valid over water under the high wind speed conditions associated with design load calculations.

Within a well mixed boundary layer, the momentum flux is assumed to be constant with height, and the wind stress, τ, can be defined by Monin-Obukhov similarity theory as

$$\tau = \rho\ u_*^2 \qquad (2),$$

where ρ is mean air density and u_* is the friction velocity. Because this flux is difficult to measure directly, τ is often estimated from readily available weather data using a bulk parameterization i.e.

$$\tau = \rho\ C_{DN}\ U_{10}^2 \qquad (3),$$

where C_{DN} is the neutral drag coefficient at 10 metres, and U_{10} is the mean wind speed at 10 m. Knowledge of C_{DN} is critical for many applications in the marine boundary layer (see Geernaert, 1987). In the context of this study, it is especially important for calculating u_* which is the scaling parameter used in wind speed and turbulence profiles. It can be easily seen from (2) and (3) that u_* is obtained by

$$u_*^2 = C_{DN}\ U_{10}^2 \qquad (4).$$

Over water, C_{DN} has been found to exhibit a linear increase with wind speed under high wind speed conditions. A typical value for this wind speed dependence is

$$10^3 C_{DN} = 0.65 + 0.067\ U_{10},\ U_{10}\ (m/s) \qquad (5),$$

based on a review of relationships given in Geernaert (1987). Charnock (1955) initially postulated that this dependence on wind speed was a result of increasing roughness length, z_0, which scaled with wind stress according to

$$z_0 = A\, u_*^2/g \quad (m) \qquad (6),$$

where g is acceleration due to gravity. In a review paper, Garrat (1977) suggested A = 0.0144. However, as Geernaert et al. (1987) point out, equation (6) indicates that C_{DN} must increase *nonlinearly* with wind speed. Results from a number of recent data sets led Geernaert et al. (1987) to conclude that C_{DN} depended to a large degree on the local wave field, and that Charnock's relation was inadequate for describing wind drag. They went on to show that wave age, defined as C_0/u_* where C_0 is wave phase speed, correlated better with C_{DN} than wind speed. For the special case of deep water, C_0/u_* can be computed from

$$(C_0/u_*)^2 = g\, H_s/(2\beta^{\frac{1}{2}}u_*^2) \qquad (7),$$

where H_s is significant wave height (m) and β, the Phillips coefficient, was assumed to have a value of 0.012. From detailed wind flux measurements in the North Sea (water depth 30 m), Geernaert et al. (1987) found the following best fit relationship between the drag coefficient and wave age

$$C_{DN} = 0.0148\ (C_0/u_*)^{-0.738} \qquad (8),$$

where swell is minimized i.e. $C_0/u_* < 40$. This expression was also found to provide a good fit to an independent data set obtained in a shallow water environment with a water depth of 15 m. Equation (8) indicates that C_{DN} is larger for growing seas (small C_0/u_*) than where seas are in equilibrium or decaying (large C_0/u_*). Because C_0 is a function of water depth as well as significant wave height and u_*, equation (8) also indicates that under moderate to high wind speeds, C_{DN} should vary considerably with water depth. Geernaert et al. (1987) showed that this effect could account for much of the difference in published C_{DN} results. They also showed that equations such as (5) were only appropriate if the sea state was nearly in equilibrium with the wind.

Under similarity theory, the nondimensionalized wind speed variance (also the square root of the area under the spectrum or the rms of turbulent fluctuations), σ, is directly proportional to the friction velocity i.e.

$$\sigma/u_* = A \qquad (9).$$

Forristall (1987) found an average value for A of 1.92 from wind data collected over a height range of 13 to 85 metres above sea level at the WEST SOLE platform, while Geernaert et al. (1987) found a value of 2.24 from measurements made 33 m above sea level in the North Sea. The significance of equation (9) is that it can be used to estimate σ (and turbulence levels) from u_*. This is the basic theory behind the universal over-water gust factor approaches proposed by Forristall (1987) and McClintock et al. (1987). These approaches are described in more detail below.

2.1 Universal offshore gust factor method of Forristall (1987):

Forristall's method assumes neutral conditions where the wind profile over water is described by

$$u(z) = u_*/k\ \ln(z/z_0) \qquad (10),$$

where $k = 0.4$, and z_0, the roughness length, is estimated from Charnock's (1955) relation given in (6). A short iterative technique was used to estimate u_* given any $u(z)$ in the boundary layer.

According to similarity theory, wind spectra at a height z in the boundary layer, are universal functions of atmospheric stability if compared with a nondimensional frequency

$$f = nz/U \tag{11},$$

and normalized by the square of the friction velocity

$$\hat{S} = nS/u_*^2 \tag{12},$$

where n in equations (11) and (12) is the frequency given in Hz. Forristall's method is based on the assumption that there is a universal spectral shape applicable for high wind speeds over the open ocean. If the nondimensional scaling given by equations (11) and (12) is correct, then spectra taken with different mean velocities should be equal within the limits of statistical variability. Forristall tested this assumption with a number of spectra observed under high wind speed conditions, and found that this was not the case. However, he was able to collapse spectra to the same form by scaling to the variance such that

$$\hat{S} = nS/\sigma^2 \tag{13}.$$

When applying equations (11) and (13) to wind spectra from different elevations on the WEST SOLE platform, Forristall found that using the actual measurement height as the length scale did not work for elevations greater than 40 m. Forristall argued that there is evidence in the literature supporting the use of a constant length scale for elevations greater than about 50 m, and concluded that a constant length scale was appropriate above 40 m. This was subsequently used in fitting models to measured spectra. The 'blunt' model

$$nS/\sigma^2 = Af/[(1+Bf)^{5/3}] \tag{14},$$

was found to have the best least squares fit to the observed spectra with averaged values of $A = 42.0$ and $B = 63.0$. Over-water wind spectra can now be derived from an estimate of σ^2. From an investigation of the variation of σ and u_* during storms, Forristall found that the variance was not a simple function of wind speed, and that surface roughness was likely playing a role. Since a wave height effect is already included through z_0, Forristall hypothesized that it was the deviation of wave height from some nominal value that was important in determining the variance of wind speed. Assuming that the nominal significant wave height, H_n, could be expressed as a simple function of wind speed by $H_n = 0.015\ U_{10}^2$, Forristall defined a wave factor, w, by

$$w = 1 + [(H_s - H_n)/(2H_n)] \tag{15}.$$

Replotting σ/u_* versus wave factor, Forristall found that the turbulence intensity increased linearly with wave factor, and that

$$\sigma/u_* = 3.0\ w \tag{16},$$

gave a reasonable fit to the data. Assuming that wind speed can be described as Gaussian noise with a spectrum given by equation (14), a low pass filter can be used with a variable averaging time, t (sec), to obtain the maximum wind speed series. The design gust is then the expected maximum of the filtered wind speeds, which

according to Forristall, should follow a Rayleigh distribution. The expected maximum wind speed, u_m, over time duration, T, is given by

$$u_m(t) = U(T) + G\,\sigma \qquad (17),$$

where $$G = [(2 \ln N)^{0.5} (1 + \gamma/(2 \ln N))\, I] - 1 \qquad (18),$$

and

$N = T/t$
$\gamma = 0.5772$
$I^2 = 1 - (f_0 B)^{-5/3}$, $f_0 > 1/B$
$f_0 = zn_0/U(T)$
n_0 = cutoff frequency = $0.44/t$.

The above approximation for I is only a good estimate for gust durations of ~5 seconds or less. Where it is not valid, G can be estimated from an exact solution provided by Forristall in Figure 2.1 (for T=3600 sec). The gust factor for a particular gust duration is computed from $u_m(t)/U(T)$. The wind speed distribution factor, G, depends on the ratio of height to wind speed, as well as the filter frequency which is equivalent to applying a moving average of duration t.

2.2 Universal offshore gust factor method of McClintock et al. (1987):

The method proposed by McClintock et al. (1987) is based on the assumption that σ/U is more or less constant over the open ocean under high wind speed conditions. From the nondimensional frequency in equation (11), they show that record length, T, can be varied to ensure that any wind sample taken from within the boundary layer has an equivalent estimate of the variance of the horizontal wind spectrum. The lowest value for n in a wind speed record, n_m, was obtained from

$$n_m = z/UT \qquad (19),$$

where T is the length of wind record in seconds. As a guideline for selection of data sets for gust analysis, McClintock et al. suggested that n_m should be less than about 10^{-3} to have a reliable estimate of σ. They pointed out that the individual values of z, T and U must also be assessed e.g. synoptic scale contamination is a problem with large values of T; the edge of the boundary layer can be reached when z approaches 100 m; and low values of U are of little practical interest for design studies.

Using the above criterion, McClintock et al. (1987) selected data from several offshore locations and computed a set of gust ratios, G_i, for each time-series from

$$G_i = u_i/U \qquad (20),$$

where u_i was the wind speed averaged over 1 sec. In the absence of flow distortion effects, the G_i were assumed to be normally distributed. The standard deviation of each set of G_i was obtained (σ_{G_i}), and a pooled estimate derived of σ_{G_i} (equivalent to the turbulence intensity σ/U). To combine σ_{G_i} values from runs with different values of n_m, σ_{G_i} was scaled so that each run would have $n_m = 10^{-4}$. The scaling was performed using a typical over-water spectrum from Large (1979), and yielded an average value for σ/U of 0.102 ±0.027. Gust factors were computed from σ_{G_i} by assuming gust ratios were normally distributed. The maximum one second gust in a given time period, T, was estimated from the normal probability distribution by

$$G_i = [-0.0208 \ln ((2\pi)^{0.5} f)]^{0.5} + 1,\ f < 1/(2\pi)^{0.5} \qquad (21),$$

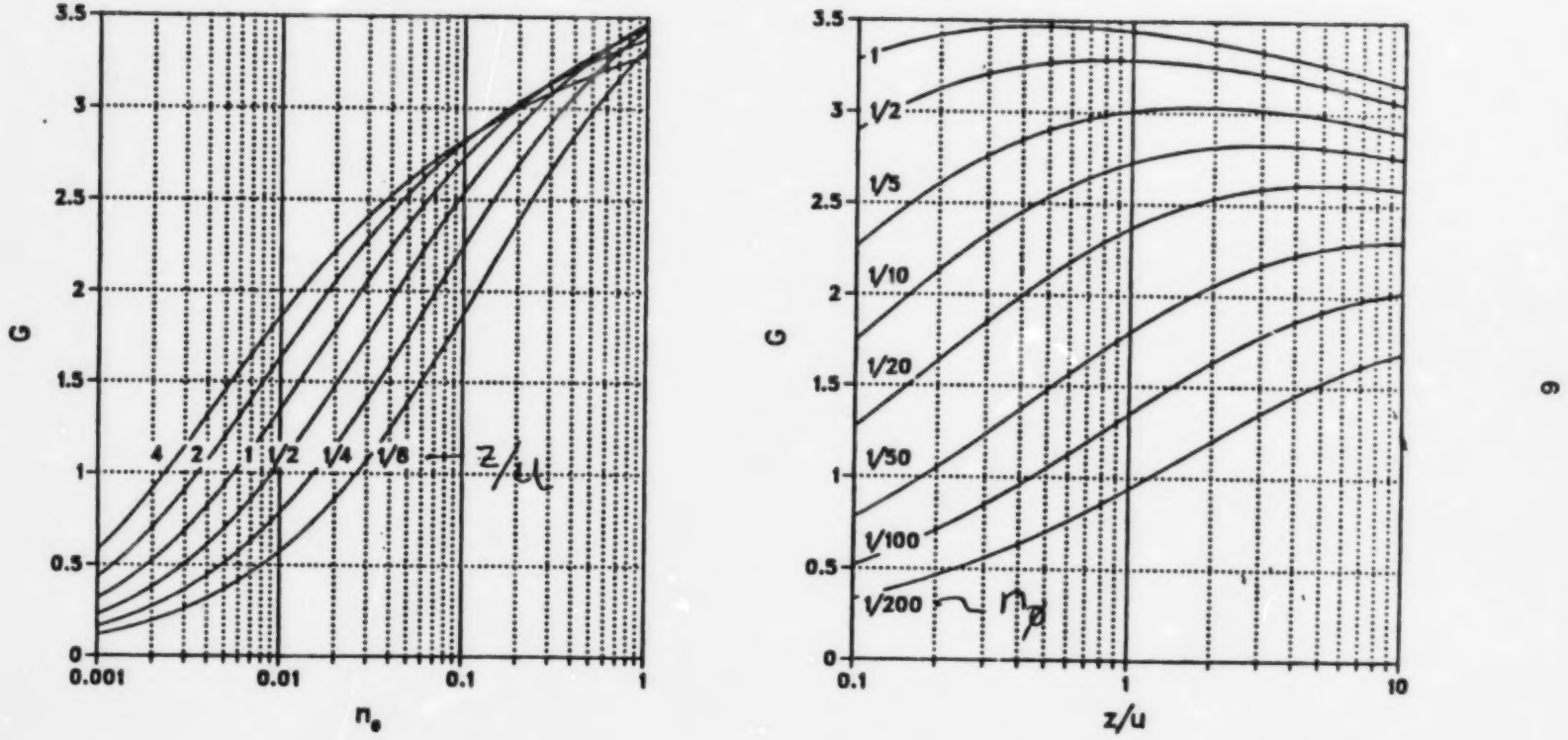


Figure 2.1: Variation of Forristall's 'G' parameter with frequency and z/U. Note that this set of results used T=3600 sec. From Forristall (1987).

where f = 1/T. For example, a value of f = 1/3600 corresponds to the probability of encountering the maximum one second gust in a one hour period. It should be noted that McClintock et al. used a fixed gust duration of 1 sec in their analysis, therefore equation (21) is only applicable for one second gusts.

There are a number of important questions raised in the above discussion which warrant further investigation, in particular, the assumption of McClintock at al. (1987) that σ/U is constant in the boundary layer. Both Forristall (1987) and Geernaert et al (1987) found that σ/u_* showed less dependence on wind speed than σ/U, which suggests σ/u_* is more suitable for predicting offshore gusts. However, the assumption of a constant σ/u_* in the marine boundary layer still needs to be investigated, as does the role of sea state in turbulence. These items are examined in Sections 4.0 and 5.0.

3.0 DATA SETS

3.1 WEST SOLE Platform:

The West Sole Wind Structure Project (Wills, 1982) was initiated in the late 1970's to obtain more information on offshore winds. The main objective was to collect information on variation of mean wind speed and turbulence with height to assist in the calculation of wind loads on offshore structures. Wind speed information was collected from the WEST SOLE "A" gas production platform located in the southern North Sea (53.7°N, 1.2°E) approximately 70 km off the English coast in -25 m water depth. Two sets of anemometers were mounted at seven levels on the radio tower, a typical open lattice structure with excellent exposure to the south at all levels (Fig. 3.1). There was some obstruction to lower elevations from the north, and a narrow band of shelter from the west. Specifically, the anemometers were unobstructed at all levels for winds from 66.5° to 246.5°, unobstructed above 40 metres for winds from 336.5° to 66.5°, and obstructed at all levels for winds from 246.6° to 336.5°.

The lightweight, cup-type "Porton" anemometer manufactured by Vector Instruments was used. This is reasonably fast acting, with a distance constant of 5 metres e.g. in a 10 m/s wind, the time constant is 0.5 seconds, which means that it responds to about 90% of the turbulent energy in the atmospheric boundary layer (Wills, 1982). Direction was measured to the nearest 22.5° centred on N, NNE etc. Anemometers were mounted on the end of 3 metre long steel booms to reduce flow distortion effects from the tower.

Wind data were collected in fast and normal modes. In normal mode, the data logger collected samples of anemometer output every 0.5 seconds, and calculated their mean, rms and maximum 3 sec gust over a 3 minute period. This data yielded the mean properties of the wind. Fast mode was triggered by the main program to capture instantaneous samples of wind speed data every 0.2 sec. These data were collected for approximately 2.5 hours provided wind speed remained above the required threshold (approximately 10 to 20 m/s), and contain information on instantaneous variations in time and space, turbulent eddy behaviour etc. (Wills, 1986). The project extended from November 1978 to August 1985, and yielded approximately 900 days of "normal" mode data, and 50 "fast" samples of 2 to 2.5 hours duration.

Flow distortion effects were investigated through wind tunnel testing of a 1:75 scale model of the platform, and through the application of a simple theoretical model of inviscid flow. The theoretical model results were used to correct flow distortion effects at the upper 4 levels of the mast, while the wind tunnel results were used for the remaining levels where the platform was the main source of flow

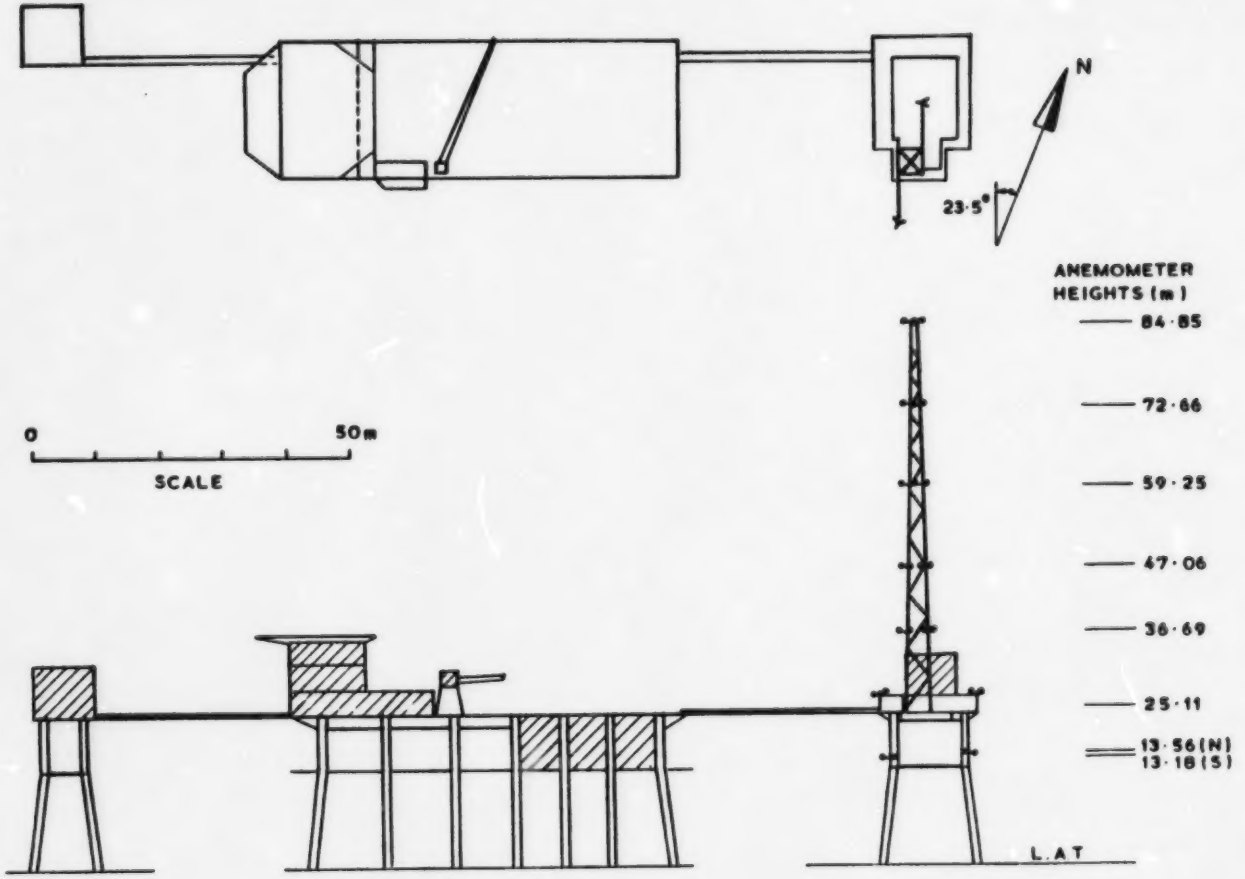


DIAGRAM OF WEST SOLE GAS PLATFORM SHOWING POSITION OF RADIO MAST

Figure 3.1: Location of anemometers on WEST SOLE platform. From Wills (1982).

distortion. It should be noted that the correction factors only apply to the mean wind speed, and not the variance. This has important consequences for gust factor analysis as will be seen later. Additional details of the flow distortion correction procedures are given in Wills (1982).

Air temperature data were collected at 25.1 and 84.9 metres above sea level, where sea level is defined as the Lowest Astronomical Tide (LAT). Mean sea level was 2.5 m above LAT (Wills, 1987). All elevations in this report are made with respect to LAT following Wills (1982, 1986). Wills (pers. comm.) indicated that the lower level temperature sensor was sheltered from the north and may not be reliable.

Due to logistical problems, sea-surface temperature data were unable to be collected from the WEST SOLE platform. Wills et al. (1986) used 5-day climatological mean sea-surface temperature values from the British Meteorological Office Historical Sea Surface Temperature dataset to estimate atmospheric stability. However, these data may differ significantly from actual sea-surface temperature conditions at the platform.

Wave data were measured with a wave staff situated beside one of the platform's legs. A number of problems were experienced with the staff, and Wills (1986) indicated that this was the main reason why no attempt had been made to correlate wind and wave data from the WEST SOLE platform. Wave data were not obtained for this study.

30 "fast" samples were obtained for gust analysis in this study. These are summarized in Table 3.1. Levels are numbered 1 to 7 from top to bottom with elevations of 84.9, 72.7, 59.3, 47.1, 36.7, 25.1 and 13.4 m

3.2 BEDFORD TOWER:

A detailed oceanographic and meteorological data set was collected from a moored, floating tower by the Bedford Institute of Oceanography (BIO) over the period 6 June, 1976 to 17 February, 1978. The buoy was located 10 km off the east coast of Nova Scotia (44.5°N, 63.4°) in 55 m of water. The fetch ranged from 10 km for winds from the north-northwest, to unlimited fetch for winds from the south and east. Wind speed was measured with a number of different instruments at 13.4 m above sea level. However, the data obtained for gust analysis were from a Mark 8 thrust anemometer which measured all three wind components. Further information on the instrumentation is presented in Smith (1980).

The wind data used for this study consisted of 20 runs of 40 minute time series of the horizontal wind component from Smith and Chandler (1987). The data had been low pass filtered with a cutoff at 11 Hz, and were digitized at a rate of 20 samples per second. The mean and trend had also been removed, leaving a time series of fluctuations. The 20 runs had mean wind speeds ranging from 12 to 23 m/s.

3.3 BOW DRILL 3:

More than two years of detailed environmental data from the drilling platform BOW DRILL 3 have been archived on magnetic tape by Husky/Bow Valley East Coast Project (HBV). The data were measured while the BOW DRILL 3 was involved in exploration activities on the Grand Banks, and consist of wind, current, wave and temperature observations. The data contain 20 minute bursts of instantaneous values every 3 hours, and sets of derived parameters every 10 minutes. The instantaneous data consist of 1 sec values of wind speed, wind direction, barometric pressure, heave, pitch, roll and wave height (McClintock et al., 1987). Initially, only wind speed data were obtained for this study. However, air temperature, sea temperature and

Table 3.1

Summary of 30 wind runs from WEST SOLE platform.

Run ID	Date (GMT)	Levels with incomplete data	Ta(°C) 84.9m	Ta(°C) 25.1m	Ts(°C)	U (m/s)	Dir	Exp
2_3	781214**		*	*	8.0	11.1	109	U
3_3_1	79031501		*	*	5.5	19.0	047	P
4_3	79041912		10.5	8.5	6.5	15.4	270	O
5_3	79052415		10.4	9.3	9.0	15.0	156	U
7_3	800218**		*	*	5.5	13.0	127	U
10_1	801023**	5,7	*	*	12.5	21.1	225	U
12_1	810203**	1	*	*	5.5	14.7	280	O
14_1_1	81112003		*	*	10.2	17.7	194	U
14_2	81112319	1,4,7	*	*	9.5	20.6	299	O
15_1	82021216	4	7.8	6.2	5.0	17.8	175	U
15_2	82030302	4	*	*	5.2	21.9	224	U
17_1_1	82110106		13.6	12.3	11.2	17.2	203	U
18_1_1	82111717	6	8.4	7.8	10.6	17.1	270	O
19_1	82111818	6	11.0	10.1	10.6	17.3	270	O
21_1_1	83011916	2,6	5.5	5.2	5.5	19.3	339	P
21_2	83020110	1,2,3,4,6,7	5.2	4.7	5.3	32.4	269	O
23_1	83042019	5	7.5	6.5	5.9	20.4	119	U
24_1	83060400		*	10.7	9.4	13.9	178	U
25_1	83062822	5	14.3	12.4	12.0	13.9	262	O
26_1_1	83090214		17.7	16.8	16.2	17.2	185	U
26_2	83091117	5	12.0	11.6	14.0	24.0	330	O
27_1	83112514	1	10.7	9.9	10.1	18.8	225	U
27_2	84010220		9.8	8.9	6.5	21.9	237	U
28_1	84012606		3.9	3.9	5.4	18.2	136	U
29_1	84012610		4.3	4.3	5.4	18.8	157	U
30_1	84032410		6.0	5.3	4.2	21.4	135	U
31_1	84101805		12.9	12.2	12.8	20.6	180	U
32_1	84110316		8.7	8.3	11.6	19.9	228	U
33_1	85032713	3,5	4.2	5.2	5.8	14.3	332	O
34_1	85052002	3,5	6.5	6.4	6.8	17.4	311	O

* - Missing information
Ts - Sea surface temperature estimated from climatology.
Ta - Air temperature.
U - Mean wind speed at highest operational anemometer.
Dir - Average wind direction over sample.
Exp - Exposure codes: U-unobstructed, 66.5° to 246.5°
P-obstructed below 40 metres, 336.5° to 66.5°
O-obstructed all levels, 246.6° to 336.5°

wave height data reported in the 3-hourly synoptic weather code were subsequently obtained to investigate stability and wave height influences on over-water gusts.

The wind data were measured by a W102-P (Weather Measure Corp.) anemometer with a distance constant of 1.9 m, accurate to 3% for wind speeds above 9.1 m/s. The anemometer was mounted on top of the derrick approximately 82.6 m above mean sea level, with an unobstructed exposure. Gust analysis was carried out with data recorded over the period January 3 to February 2, 1985, from the wellsite North Ben Nevis P-93 located on the eastern Grand Banks (46.7°N, 48.4°W) in ~100 m water depth. The wind speed runs consisted of two 10 minute bursts, separated by a 45-90 sec gap. These were treated as one single 20 minute sample following McClintock et al. (1987).

4.0 DATA ANALYSIS

Gust analysis was carried out in two parts. First, the "traditional" gust factor approach was used to investigate gust factor variation with gust duration, measuring interval, elevation, wind speed, significant wave height and stability. Second, an evaluation was carried out of the magnitude and variation of turbulence intensity over water.

4.1 Gust factor analysis:

The traditional approach to gust analysis defines a gust factor, G(t,T), as:

$$G(t,T) = u_{max}(t,T)/u(T) \qquad (22),$$

where u_{max} is the maximum average wind speed of duration t in the measuring interval T ($T >> t$), and u(T) is the mean wind speed over the measuring interval T. For example, G(1,3600) = 1.3 indicates that the maximum 1 sec average wind speed in an hour was 30% larger than the mean hourly wind speed. Gust factors can be computed for the downwind (u_1), crosswind (u_2) or vertical (u_3) wind components. Smith and Chandler (1987) present results for G_1, G_2 and G_3. However, as turbulence in u_2 and u_3 are small compared to u_1, these are usually neglected when computing gust factors for offshore structures.

In this study, u_{max} was computed from block averages of duration t. Strictly speaking, a running mean should be used. However, the blocks did not appear to introduce significant error (see Fig. 4.1) and cut down on processing time. The computed gust factors were then analyzed to characterize their variation with respect to gust averaging interval, t, measuring interval, T, elevation, z, atmospheric stability, significant wave height, H_s, and mean wind speed, u(T). Only unobstructed wind runs were used from the WEST SOLE platform.

4.2 Characteristics of over-water gust factors:

4.2.1 General

Mean 1 sec gust factor results for the three data sets are presented for comparable elevations in Table 4.1. Summaries for 3, 15 and 60 sec gusts are presented in Tables A-1 to A-3 in Appendix A. The WEST SOLE and BEDFORD TOWER mean gust factors are in excellent agreement, although the standard deviation of the gust factors is noticeably higher at the WEST SOLE platform. This difference is most probably attributable to the filtering and trend removal carried out on the BEDFORD TOWER data. Further evidence for this hypothesis is seen in the marked increase in gust standard deviation with increasing T at the WEST SOLE platform compared to the

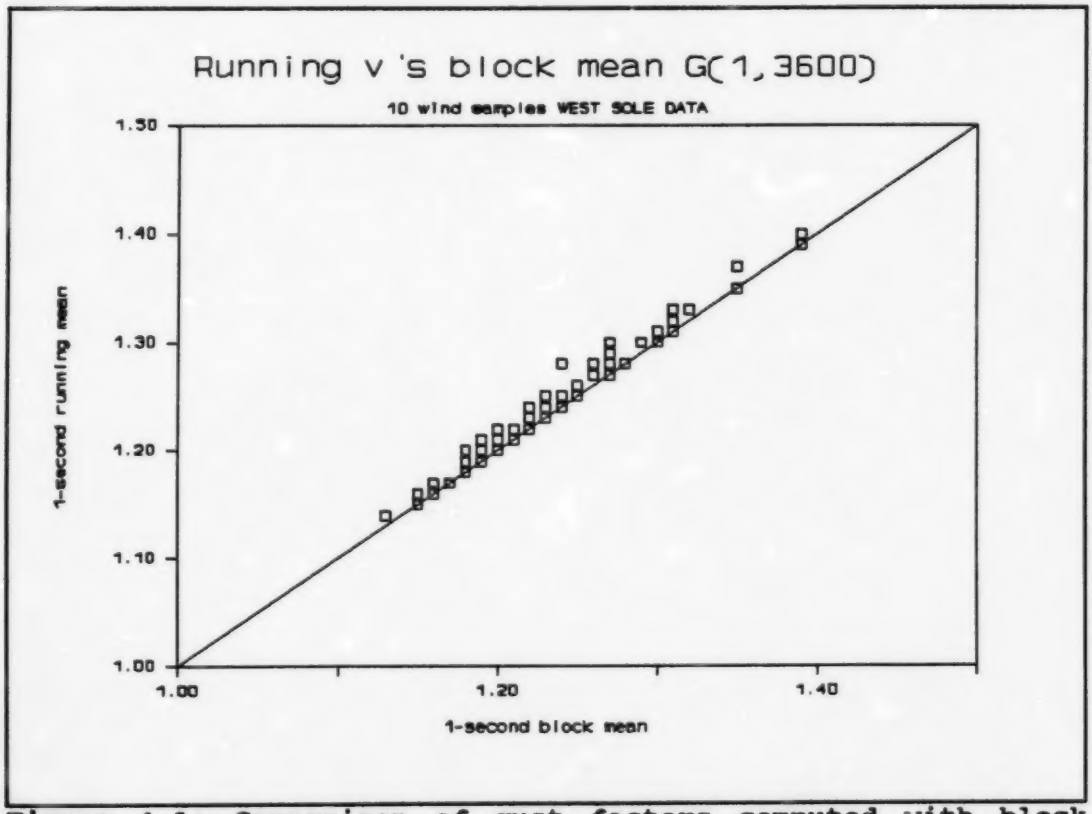


Figure 4.1: Comparison of gust factors computed with block averages and running means.

Table 4.1

Summary of 1 sec gust factors.

	WEST SOLE (13.4 m)			BEDFORD TOWER (13.4 m)		
(t,T)	n	G(t,T)	sd	n	G(t,T)	sd
(1,600)	204	1.25	0.095	77	1.26	0.046
(1,1200)	102	1.28	0.105	38	1.29	0.047
(1,2400)	51	1.32	0.126	18	1.31	0.048
(1,3600)	34	1.34	0.134	-	-	-

	WEST SOLE (84.9 m)			BOW DRILL 3 (82.6 m)		
(t,T)	n	G(t,T)	sd	n	G(t,T)	sd
(1,600)	204	1.15	0.046	248	1.21	0.066
(1,1200)	102	1.18	0.053	124	1.24	0.067
(1,2400)	51	1.20	0.060	-	-	-
(1,3600)	34	1.22	0.062	-	-	-

Table 4.2

Comparison of WEST SOLE gust factors with published values.

Source	Elev.(m)	G(60,3600)	G(15,3600)	G(3,3600)
HOUE[1]	20.0	1.25	-	-
API[1]	-	1.24	1.34	1.51
UKDOE[1]	10.0	1.17	1.27	1.37
DnV[1]	-	1.18	1.26	1.33
Mackey[1]	10.0	1.18	1.24	1.31
WEST SOLE	13.4	1.15	1.22	1.30

[1] From Dello Stritto et al. (1985)

BEDFORD TOWER. Gust factors at the BOW DRILL 3 are noticeably higher than the WEST SOLE. This could be due to a number of factors including flow distortion effects, higher waves and more frequent unstable conditions.

A comparison of the WEST SOLE hourly gust factors with recommended values for offshore locations is given in Table 4.2 (the other two sites are not included in the comparison because maximum values of T were less than 3600 sec). The WEST SOLE results show good general agreement with the Mackey formula and DnV gust factors.

4.2.2 Variation of G(t,T) with gust duration, t

Figure 4.2 shows gust factor variation with t, for comparable values of z and T at the three locations. The gust factor decreases with increasing gust duration and is able to be described by a simple power law of the form at^b, where a is the least squares estimate of G(1,T), and b is the least squares exponent. A nonlinear least squares regression procedure developed by Marquardt (1963) was used to estimate model parameters. The results show that gust factors are more sensitive to variation in t for gust durations less than about 15 sec. The lower exponent values at higher elevations also indicates that gust factors are less sensitive to changes in t with increasing elevation. Variation in T had a noticeable impact on the 'a' parameter, but little effect on the value of the exponent. The least squares equation for the WEST SOLE mean G(t,3600) results at z = 13.4 m was

$$G(t,3600) = 1.331\ t^{-0.033}, \quad 0.2 \leq t \leq 60, \qquad (23).$$

with an r^2 value of 0.981.

4.2.3 Variation of G(t,T) with measuring interval, T

Increasing T has the effect of increasing gust factors. For example, a doubling of T (600 to 1200 sec or 1200 to 2400 sec) yielded an increase in gust factor of 0.02-0.03 for all three data sets. This value is in good agreement with Smith and Chandler (1987) who found that a doubling of T produced an increase in G of approximately 0.02. All three data sets showed evidence that the impact of increasing T was slightly greater for small values of t. In addition, the WEST SOLE results showed that elevation had a small effect: a six-fold increase in T from 600 to 3600 seconds at 13.4 m resulted in an increase in G(1,T) of 0.09, while the same increase in T at 84.9 m produced a lower gust factor increase of 0.06.

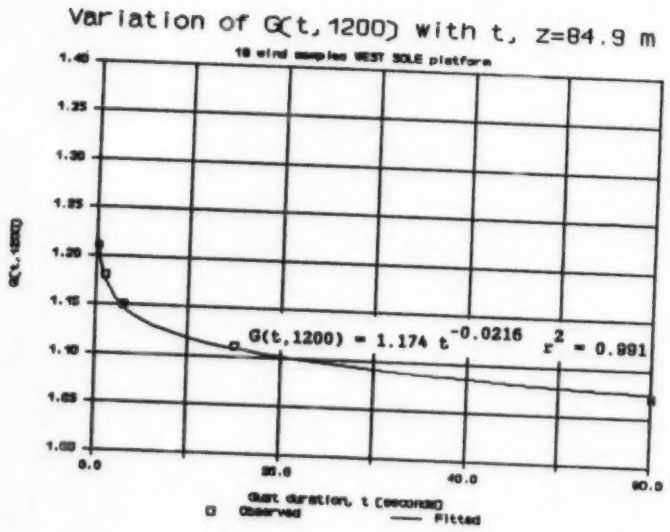
As with t, the observed results could be described with a power law model, although the exponent was positive in this case. The least squares fit to the mean WEST SOLE G(1,T) results at z = 13.4 m yielded

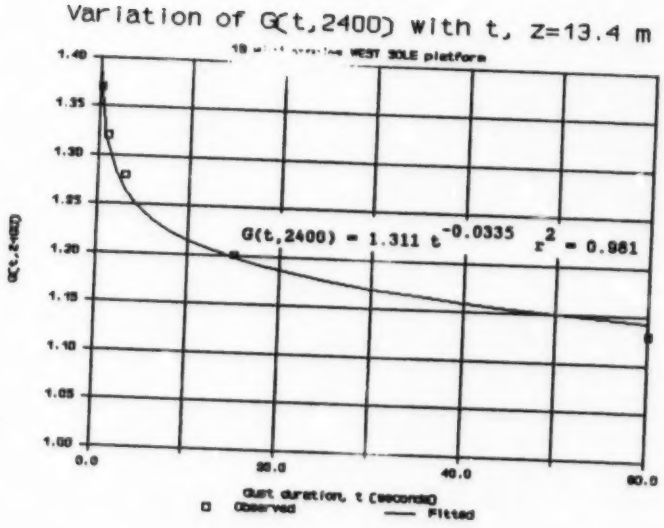
$$G(1,T) = 0.970\ T^{0.0395}, \quad 600 \leq T \leq 3600, \qquad (24),$$

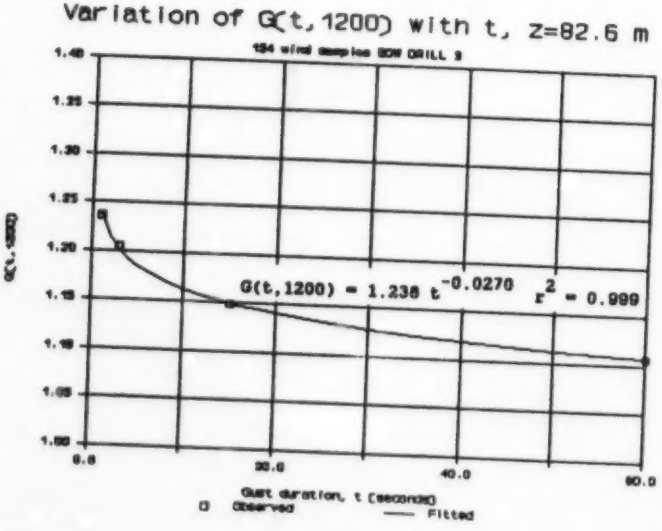
with an r^2 value of 0.997. Results were not computed for the other two locations because the shorter measuring intervals limited the number of points in the analysis. The model fit to the WEST SOLE data is shown in Figure 4.3.

4.2.4 Variation in G(t,T) with elevation, z

Variation of gust factors with elevation was only able to be addressed with the WEST SOLE data. Figures 4.4 and 4.5 summarize results for different values of t and T. A clear feature of these figures is the reduction of the gust factor with increasing elevation. A decrease in gust factors with elevation is consistent with theory in that turbulence velocities vary rather slowly within the constant shear stress layer (~100 m), but the mean wind speed decreases towards the ground. This results in an







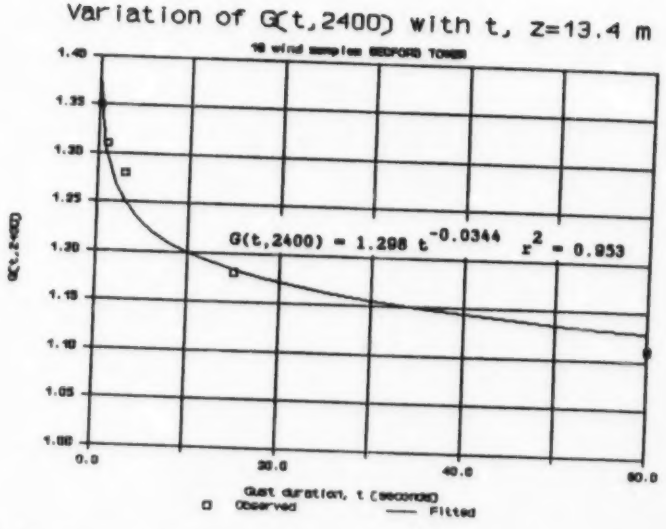


Figure 4.2: Variation of mean gust factors with gust duration at the three offshore locations.

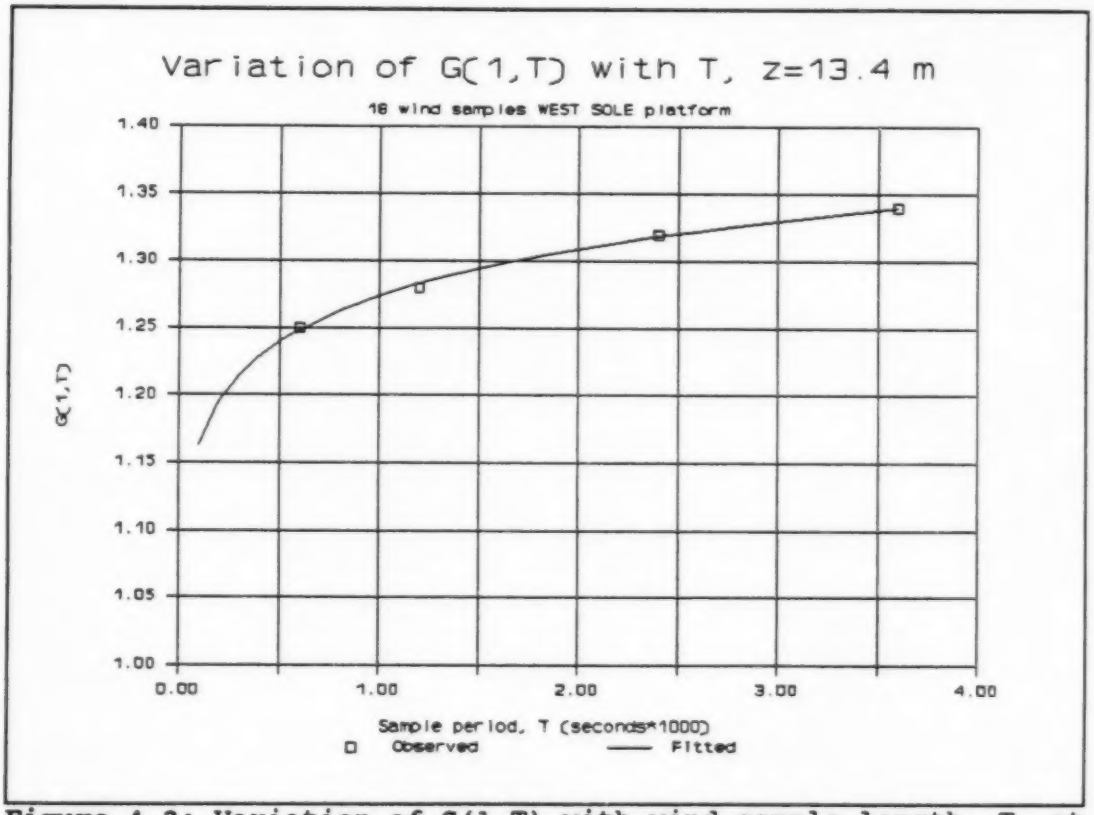


Figure 4.3: Variation of G(1,T) with wind sample length, T, at 13.4 metres elevation for the WEST SOLE platform data.

increase in turbulence intensity toward the surface. As noted previously, Figures 4.4 and 4.5 show the decreased sensitivity of gust factors to changing t and T at higher elevations. This is more noticeable for t than T.

To characterize the gust relationship with elevation, a power law was fitted to the mean gust factors

$$G_z = G_{10}\ (z/10)^b, \qquad (25),$$

where G_z - mean gust factor at elevation z metres
G_{10} - mean gust factor at 10 metres
b - exponent.

Estimates of 'b' for t = 0.2, 1, 3, 15 and 60 sec were obtained from the least-squares nonlinear regression analysis described previously. Results are summarized below in Table 4.3.

Table 4.3

WEST SOLE over-water gust height exponents (T=3600).

t	b	r^2	G_{10}
0.2	-0.061	0.98	1.42
1.0	-0.054	0.98	1.37
3.0	-0.047	0.99	1.32
15.0	-0.033	0.99	1.23
60.0	-0.020	0.97	1.16

In an earlier analysis of WEST SOLE wind data, Wills (1982) reported that G_{10} = 1.28 and b = -0.03 represented the height variation of 3 sec gust factors. The 3 sec gust results in Table 4.3 indicate slightly higher gust factors and a greater sensitivity to variation in height. This difference is due to different gust definitions: Wills (1982) used the hourly maximum 3 sec gust recorded over consecutive 3 minute periods i.e. the maximum value of G(3,180) occurring in an hour. This is not the same as G(3,3600) used in this study. Gust factor results from Goptarev cited in Roll (1965) for G(t,600) where t is unknown but < 1 sec, yielded b = -0.054 and G_{10} = 1.32. Corresponding G(1,600) values from unobstructed wind runs from the WEST SOLE platform were somewhat lower at -0.045 and 1.27 respectively. It was discovered during this analysis that gust height variation was very sensitive to flow distortion effects, particularly for shorter gust durations, because most of the distortion occurred at lower levels. For example, where the WEST SOLE data were not screened for obstructions to the wind flow, G(0.2,3600) values for 'b' and G_{10} were -0.078 and 1.49 respectively.

4.2.5 Variation of G(t,T) with stability

Gust factor variation with stability was able to be investigated for the WEST SOLE and BOW DRILL 3 data. Wills et al. (1986) inferred stability information at WEST SOLE from the air-sea temperature difference. However, attempts to fit individual WEST SOLE wind profiles with the boundary layer model of Walmsley (1988)[1] indicated that actual sea-surface temperatures could be several degrees warmer or colder than

[1] See Appendix B for a comparison of modelled and observed wind profile data.

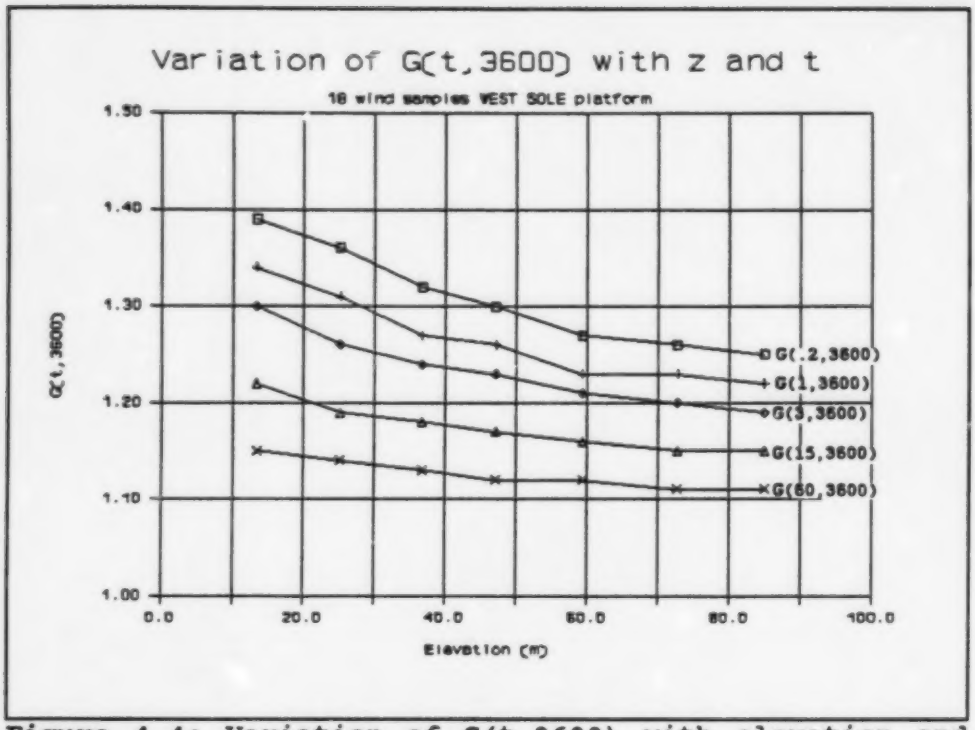


Figure 4.4: Variation of G(t,3600) with elevation and gust duration, t, for 18 unobstructed 2-hr wind samples from the WEST SOLE platform.

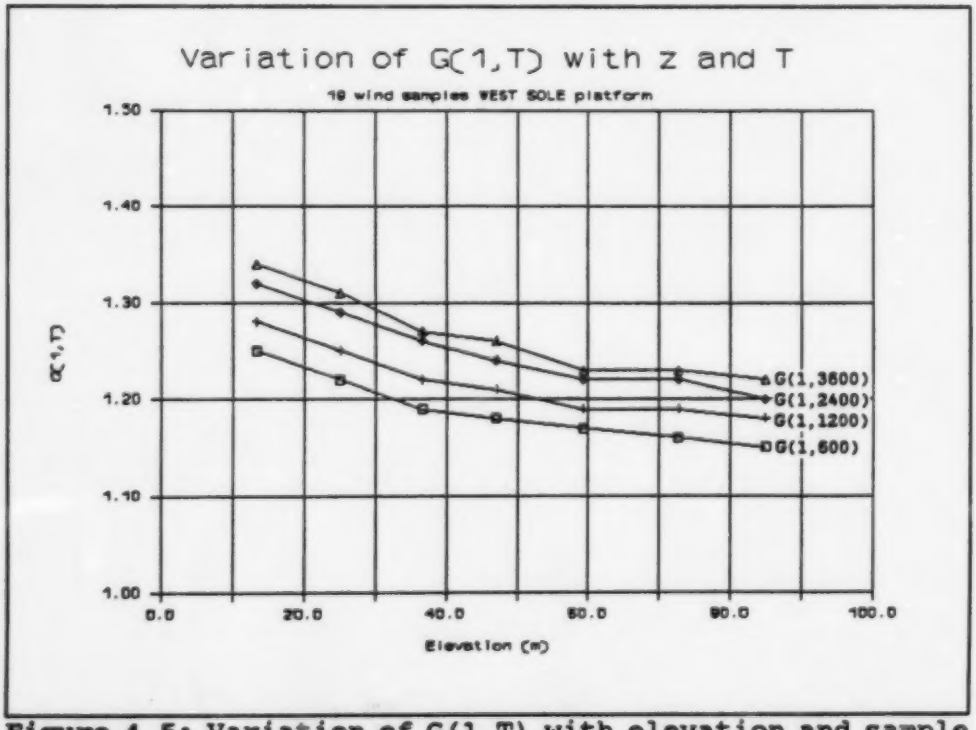


Figure 4.5: Variation of G(1,T) with elevation and sample length, T, for 18 unobstructed wind profiles from the WEST SOLE platform.

the sea-surface climatology values supplied with the wind data. To eliminate this source of error, stability information for the WEST SOLE platform was inferred from the gradient form of the Richardson number (Ri) computed with air temperature and wind speed data collected at 25.1 (z_1) and 84.9 (z_2) metres above sea level from

$$Ri = [g((\theta_2-\theta_1)/dz)] \; / \; [Ta((u_2-u_1)/dz)^2] \qquad (26),$$

where g = acceleration due to gravity
θ = potential temperature
$dz = z_2 - z_1$
$Ta = Ta_1 + 273.16$
u = mean wind speed over 2 hours.

A summary of the Richardson number calculations are given in Appendix A (Table A-4). Results of gust factor variation with Ri are shown in Figures 4.6 and 4.7 for two elevations. While there is a large amount of scatter in the 13.4 m results, there is some indication of decreasing gustiness with increasing stability. This trend is less noticeable with increasing elevation, and the 84.9 m results show little evidence of any stability dependence. While these results are consistent with theory, they are not likely to be particularly reliable because of uncertainties in the air temperature and wind speed data measured at 25.1 m. Detailed comparisons of observed and predicted hourly wind profiles from the model of Walmsley (1988) frequently showed lower wind speeds than expected at the lower two levels of the WEST SOLE platform (13.4 and 25.1 m). This result is not inconsistent with the siting of the anemometers. Wills (1982) indicated that the two lowest level anemometers were mounted on the platform structure while the upper 5 levels were mounted on a radio mast above the platform.

As wind speed and air temperature were only measured at single elevations on the BOW DRILL 3, stability information was inferred following Wills et al. (1986) with a stability parameter, $d\theta/u^2$, which approximates the Monin-Obukhov length. The difference between the air and sea-surface potential temperatures, $d\theta$, was approximated by the air-sea temperature difference, where the air temperature was measured at a screen height of ~20 m. The results (Fig. 4.8) show little evidence of any relationship, although it is clear that unstable conditions dominated here where the opposite was true of the WEST SOLE data.

The above results agree with Smith and Chandler (1987) who found that in general, stability had a relatively small impact on gust factors measured at z = 13.4 m. However, they did notice a tendency for higher gust factors under unstable conditions where gust durations were longer (3-60 sec).

4.2.6 Variation of G(t,T) with wind speed and wave height

Wind speed should exercise an indirect effect on gust factors through its influence on sea surface roughness. It would have been desirable to investigate this effect directly by comparing gust factors and wave height data. Unfortunately, only the BOW DRILL 3 data set included wave height information. A comparison of gust factors and mean wind speeds are shown in Figures 4.9 to 4.12 for comparable elevations at the three locations. A shorter duration gust, G(0.2,600), was used for the WEST SOLE - BEDFORD TOWER comparison to increase the amount of data in the analysis.

All three data sets showed evidence of a general trend toward increasing gustiness with increasing wind speed, in agreement with Vickery et al. (1985) and Smith and Chandler (1987). However, there was considerable scatter in the BOW DRILL 3 and BEDFORD TOWER results, and the amount of variance explained by linear regression analysis was very low. The WEST SOLE data exhibited a more clearly defined variation

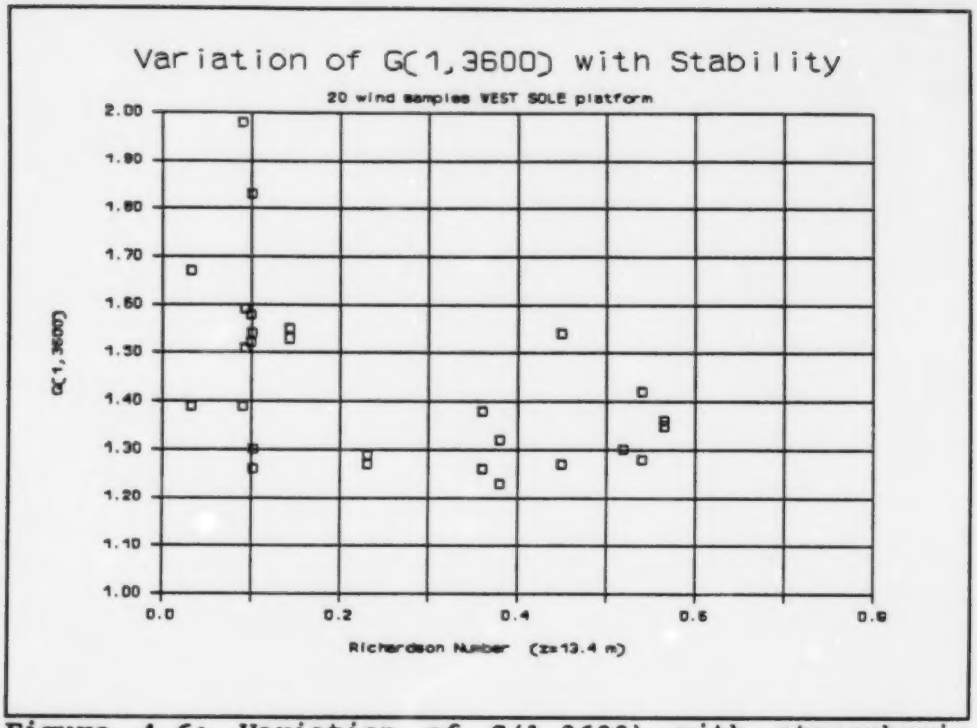


Figure 4.6: Variation of G(1,3600) with atmospheric stability at 13.4 mASL.

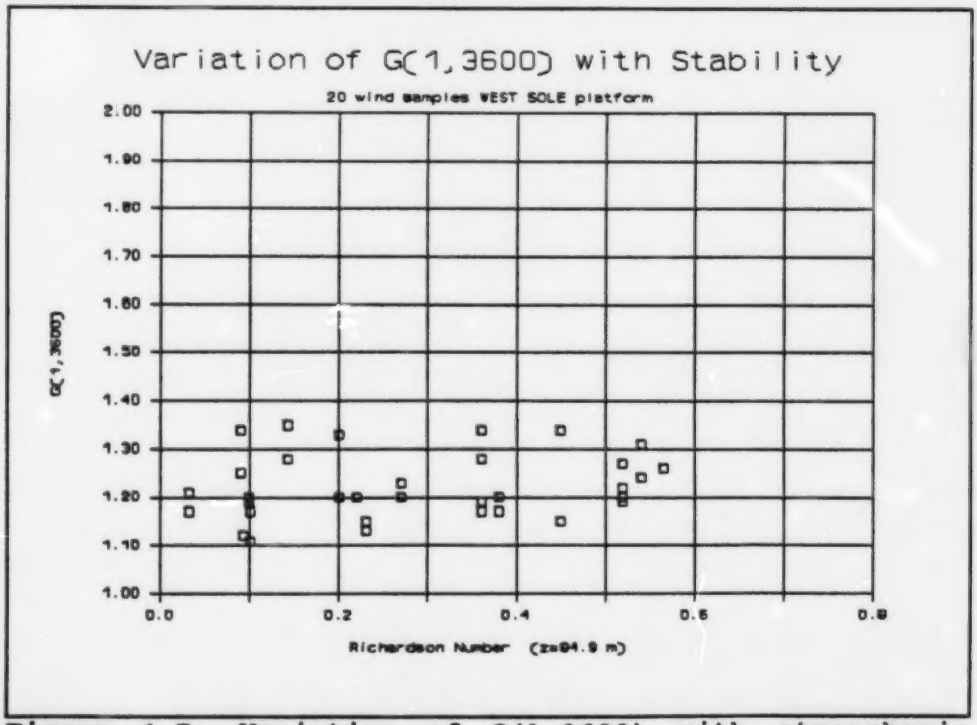


Figure 4.7: Variation of G(1,3600) with atmospheric stability at 84.9 mASL.

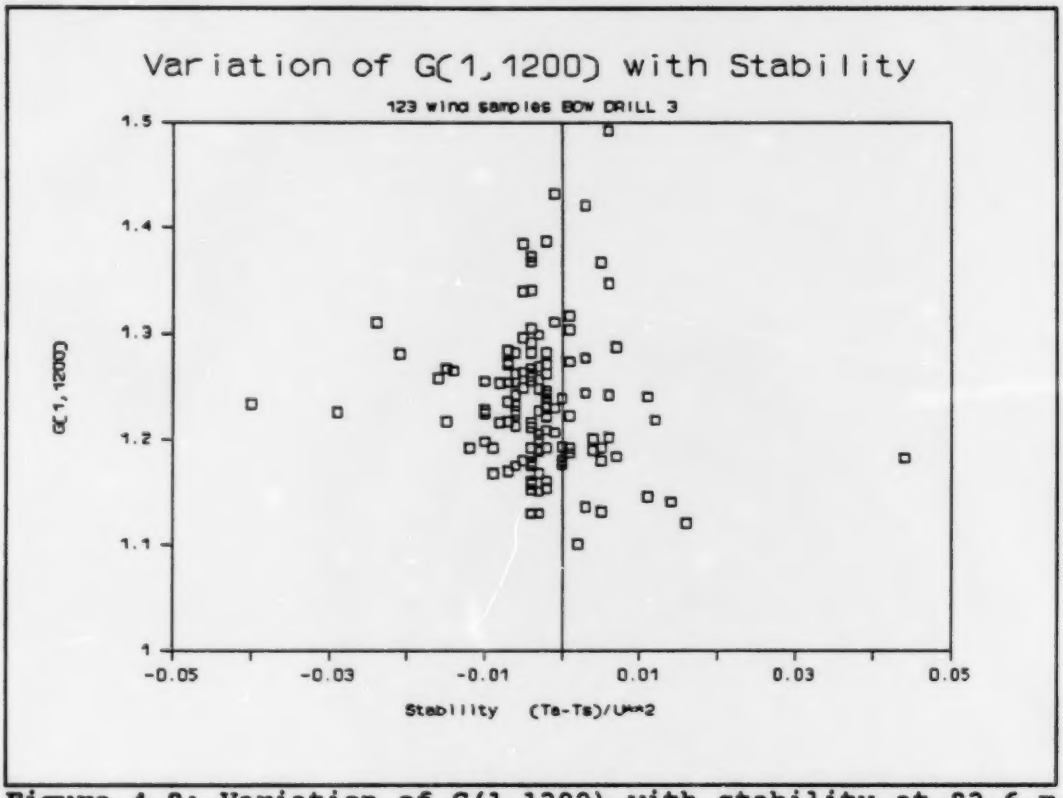


Figure 4.8: Variation of G(1,1200) with stability at 82.6 m for the BOW DRILL 3.

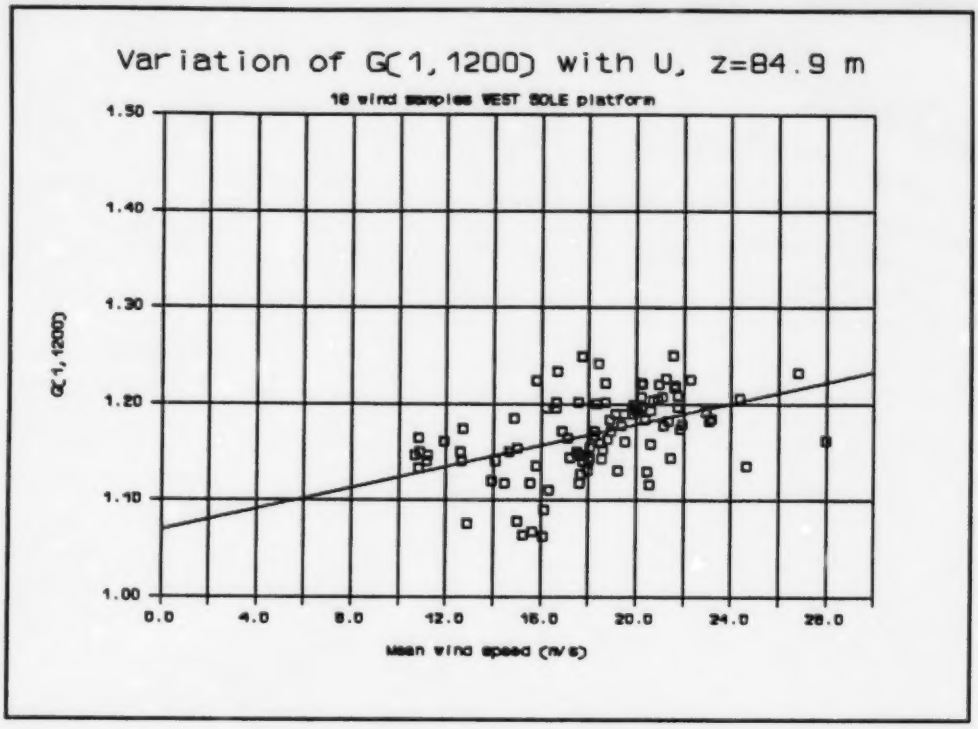


Figure 4.9: Variation of G(1,1200) with wind speed at 84.9 m for the WEST SOLE platform. The equation for the best fit line is $1.069 + 0.00547(U_{84.9})$ with $r^2 = 0.215$.

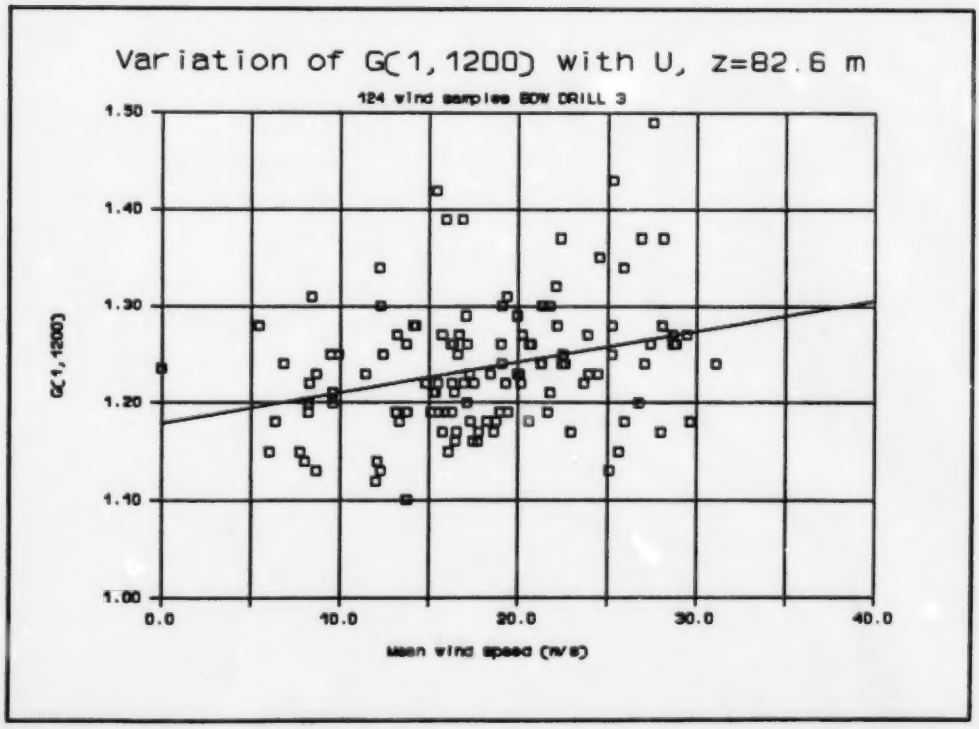


Figure 4.10: Variation of G(1,1200) with wind speed at 82.6 m for the BOW DRILL 3. The equation for the best fit line is $1.179 + 0.00317(U_{82.6})$ with $r^2 = 0.082$.

with wind speed, although the amount of variance explained was still rather low (10-30%). The greater dependence on wind speed at the WEST SOLE may be a reflection of flow distortion effects which would increase with increasing wind speed. Vickery et al. (1985) carried out a detailed wind tunnel analysis to remove flow distortion errors from wind speed and turbulence data measured from a jack-up drilling platform off the east coast of Canada (z = 53.9 m). Their corrected results exhibited very low correlations with wind speed (r^2 values less than 0.05).

An investigation of gust factor wind speed dependence for different elevations at the WEST SOLE platform revealed a decrease in the slope and the amount of variance explained as elevation increased. For example, the two best fit equations for G(1,3600) at 13.4 and 84.9 m were:

$$13.4\text{ m:} \quad 1.145 + 0.012(U_{13.4}),\ r^2 = 0.372 \qquad (27),$$
$$84.9\text{ m:} \quad 1.104 + 0.006(U_{84.9}),\ r^2 = 0.117 \qquad (28).$$

A comparison of G(0.2,3600) and G(60,3600) gust factors at 13.4 m elevation showed shorter duration gusts were more sensitive to wind speed variation:

$$G(.2,3600): \ 1.173 + 0.013(U_{13.4}),\ r^2 = 0.395 \qquad (29),$$
$$G(60,3600): \ 1.053 + 0.005(U_{13.4}),\ r^2 = 0.239 \qquad (30).$$

Vickery et al. (1985) also found a decrease in the correlation between gust factors and wind speed as gust duration increased.

Correlation of gust factors with significant wave height at the BOW DRILL 3 (Fig. 4.13) exhibited a large degree of scatter and explained no more variance than the wind speed results presented in Figure 4.10. This result is contrary to Vickery et al. (1985) who obtained much higher correlations between gusts and rms wave height (r^2 values of 0.25-0.30) than for wind speed. H_s and H_{rms} are linearly related by $H_s = 1.414\ H_{rms}$ (CERC, 1977) which means the two correlations are directly comparable. The low wave height correlations at the BOW DRILL 3 may be a result of noise in the data from flow distortion effects, or the effect of a higher anemometer height (82.6 m compared to 53.9 m in the Vickery et al. study). All the BOW DRILL 3 runs were recorded under relatively high wind speed (15-20 m/s) and slightly unstable conditions, so there is no reason to suspect that the winds were de-coupled from the boundary layer. This is an area deserving further investigation, preferably with a higher quality data set recorded at a lower elevation.

4.3 Characteristics of turbulence intensity over water:

Knowledge of turbulence intensity, σ/u_*, over water is important for modelling gust factors. Data from the WEST SOLE and BEDFORD TOWER platforms were used to investigate the magnitude and characteristics of σ/u_*, namely its variation with wind speed, elevation and stability. Investigation of turbulence intensity variation for the latter two variables was limited to the WEST SOLE data set as the BEDFORD TOWER data were recorded at a single level, and the data set did not contain the required information for computing stability.

For the WEST SOLE and BEDFORD TOWER data sets, σ was obtained from the rms of the 0.2 second wind fluctuations over 1 hour and 40 minute periods respectively. Data from the BOW DRILL 3 were not used because the raw data were measured at a lower frequency (1 Hz) and the measuring interval was only 20 minutes. The friction velocity was estimated following Forristall (1987) assuming a logarithmic wind profile and Charnock's relation for z_0.

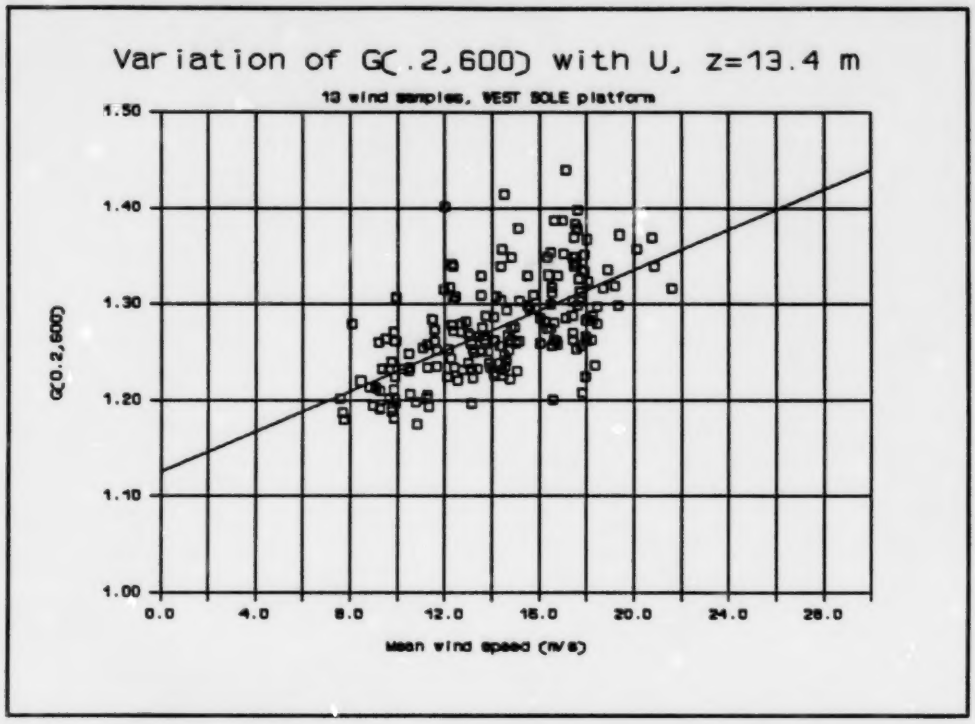


Figure 4.11: Variation of G(0.2,600) with wind speed at 13.4 m for the WEST SOLE platform. The equation for the best fit line is $1.252 + 0.0105(U_{13.4})$ with $r^2 = 0.380$.

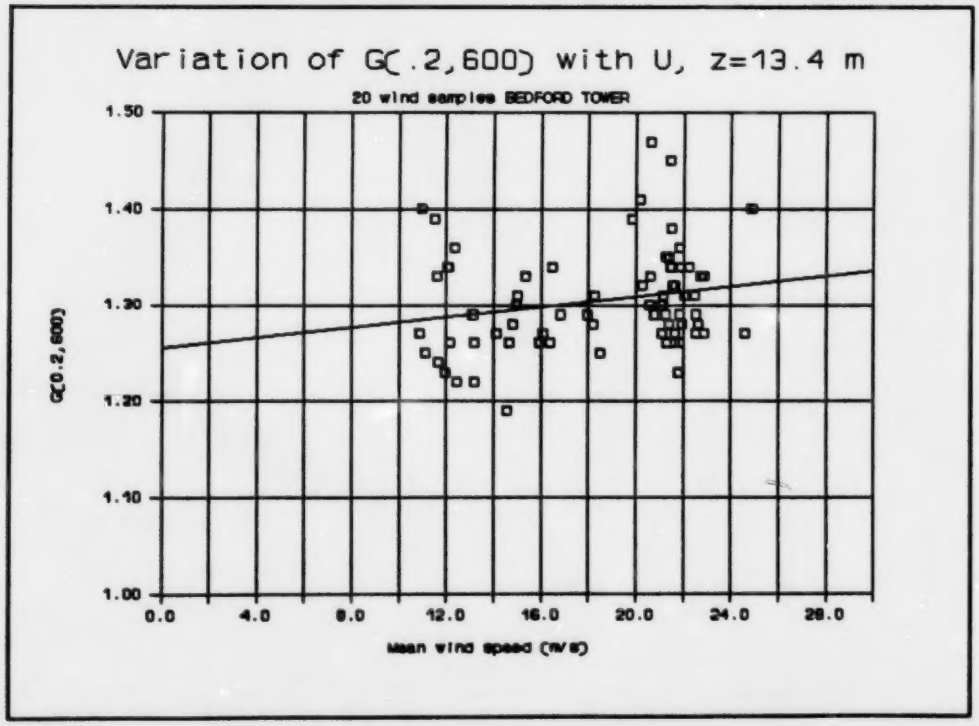


Figure 4.12: Variation of G(0.2,600) with wind speed at 13.4 m for the BEDFORD TOWER. The equation for the best fit line is $1.255 + 0.00267(U_{13.4})$ with $r^2 = 0.046$.

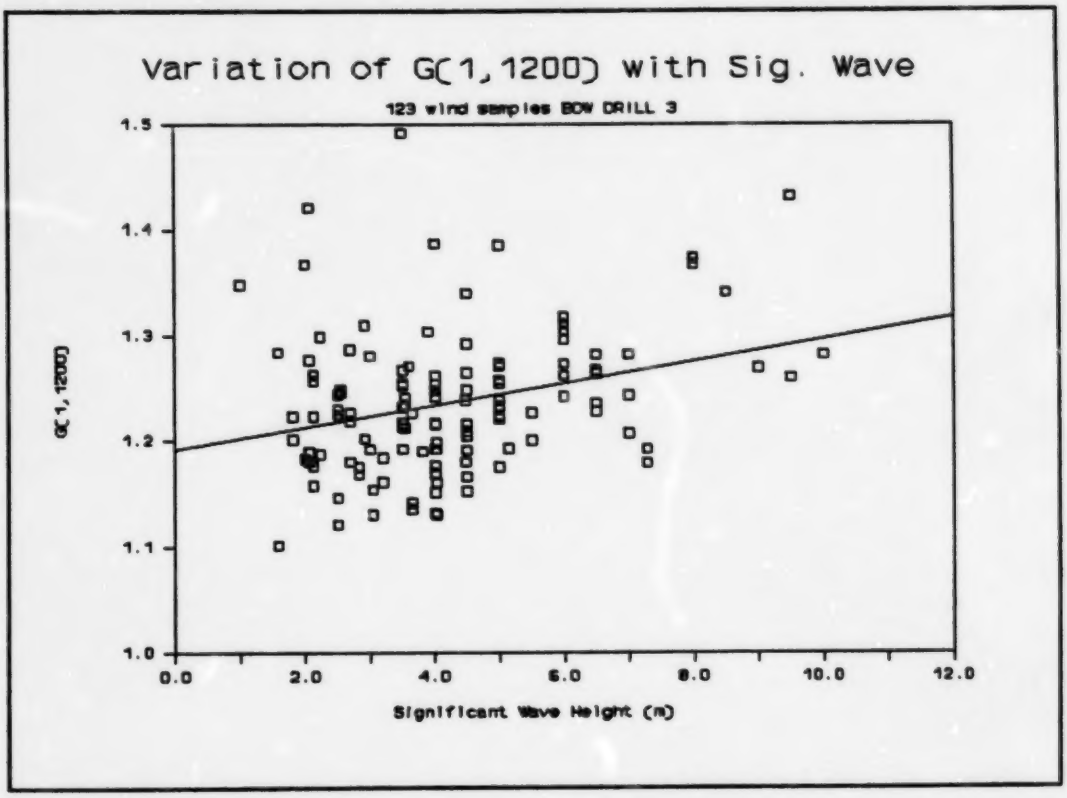


Figure 4.13: Variation of G(1,1200) with significant wave height. The best fit line shown has an r^2 of 0.08.

4.3.1 Variation of σ/u_* with wind speed

Variation of σ/u_* with wind speed at the two sites is shown in Figures 4.14 and 4.15. The BEDFORD TOWER results showed no indication of any relationship, while the WEST SOLE results for z = 13.4 m showed a slight trend toward increasing σ/u_* with wind speed. However, a best fit linear relationship only explained 13% of the variance. The results for z = 84.9 m, shown on the same figure, exhibited considerably more scatter than the 13.4 m values, with little suggestion of any dependence on wind speed. Geernaert et al. (1987) also found wind speed to have an insignificant effect on the longitudinal wind speed variance based on measurements at 33 m elevation in the North Sea. However, like Forristall (1987), they also found more of a wind speed dependence where σ was normalized against mean wind speed. The same feature was evident with the WEST SOLE data as shown by the following least squares linear relationships at z = 13.4 m:

$$\sigma/u_* = 1.943 + 0.0411\ U,\ r^2 = 0.13 \quad (31),$$
$$\sigma/U = 0.0539 + 0.0032\ U,\ r^2 = 0.38 \quad (32).$$

A similar trend was noted for the BEDFORD TOWER data although the amount of variance explained was minimal (1.6% for the σ/u_* relationship and 2.4% for the σ/U relationship). The mean value of σ/u_* over all 7 levels at the WEST SOLE platform was 2.26 ±0.39 which compares well with the mean value of 2.24 found by Geernaert et al. (1987) for the North Sea. A higher mean value of 2.58 ±0.28 was obtained from the BEDFORD TOWER site. This is closer to the mean value of 2.45 reported by Vickery et al. (1985) from an oil drilling platform near Sable Island.

4.3.2 Variation of σ/u_* with elevation

Figure 4.16 shows σ/u_* as a function of elevation for all 18 WEST SOLE exposed wind runs. The mean profile is closely approximated by a linear expression of the form

$$\sigma/u_* = 2.58 - 0.00667\ z,\ r^2 = 0.94 \quad (33).$$

95% confidence limits are shown either side of the mean value for each elevation, as well as the line $\sigma/u_* = 2.26$ (±0.387) which represents the mean value for all 7 levels. It can be seen that the line of constant σ/u_* is not significantly different from the mean over all 7 levels, justifying the use of a fixed value for σ/u_*. It can also be seen in Figure 4.16 that mean values of σ/u_* for the lower 2 levels deviate more noticeably from the line of constant σ/u_*, which is probably related to flow distortion. The same investigation for σ/U yielded similar results (Fig. 4.17) with the following least squares expression

$$\sigma/U = 0.099 - 0.00038\ z,\ r^2 = 0.92 \quad (34).$$

As with σ/u_*, the average value for σ/U (0.080 ±0.015) was not significantly different from the mean over all 7 levels. However, as noted by Forristall (1987), σ/U displays a greater sensitivity to changes in elevation e.g. a change in elevation from 13.4 to 84.9 m produced, on average, a 19.0% reduction in σ/u_*, but a 29.6% reduction in σ/U. The average value obtained for σ/U agrees well with the 0.071 value observed by Vickery et al. (1985). However, these are both somewhat lower than the 0.106 value obtained from the BEDFORD TOWER which is close to the pooled estimate of $\sigma/U = 0.104$ proposed by McClintock et al. (1987).

4.3.3 Variation of σ/u_* with stability

The above results were obtained assuming a neutral boundary layer when in fact the WEST SOLE data were typically stable. This was confirmed from vertical profiles of

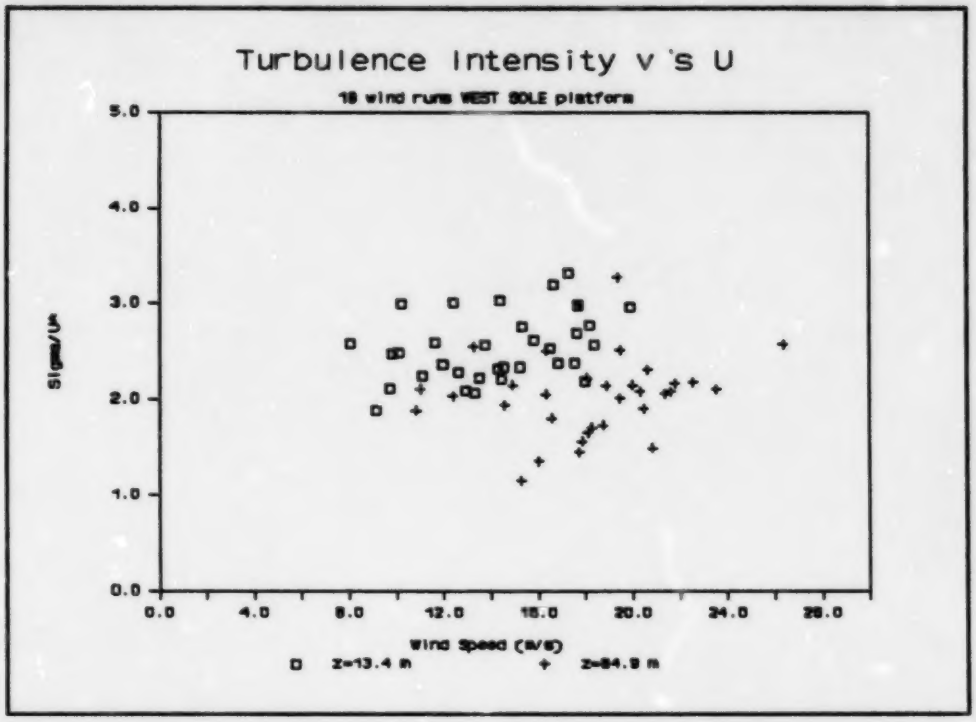


Figure 4.14: Variation of sigma/u* with mean wind speed at 13.4 m and 84.9 m for the WEST SOLE platform.

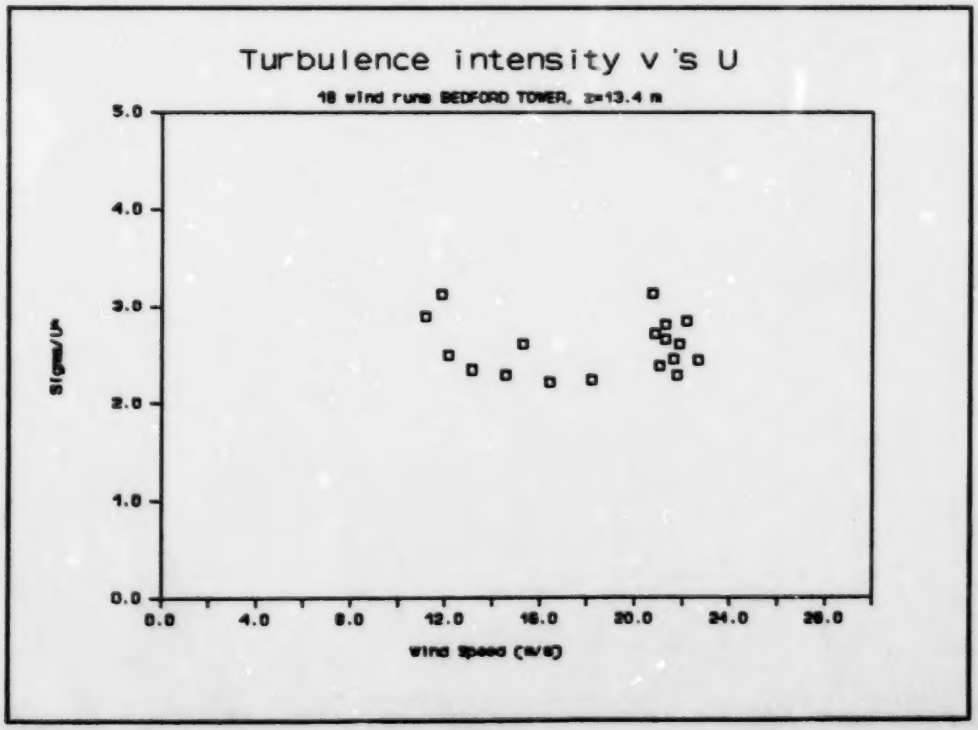


Figure 4.15: Variation of sigma/u* with mean wind speed at 13.4 m for the BEDFORD TOWER.

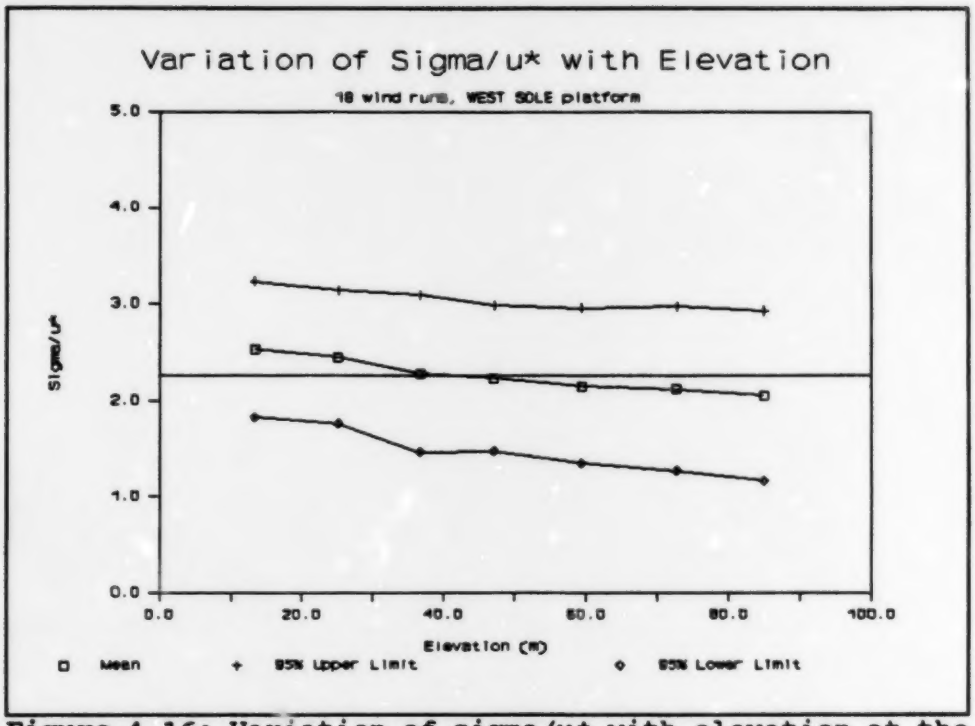


Figure 4.16: Variation of sigma/u* with elevation at the WEST SOLE platform.

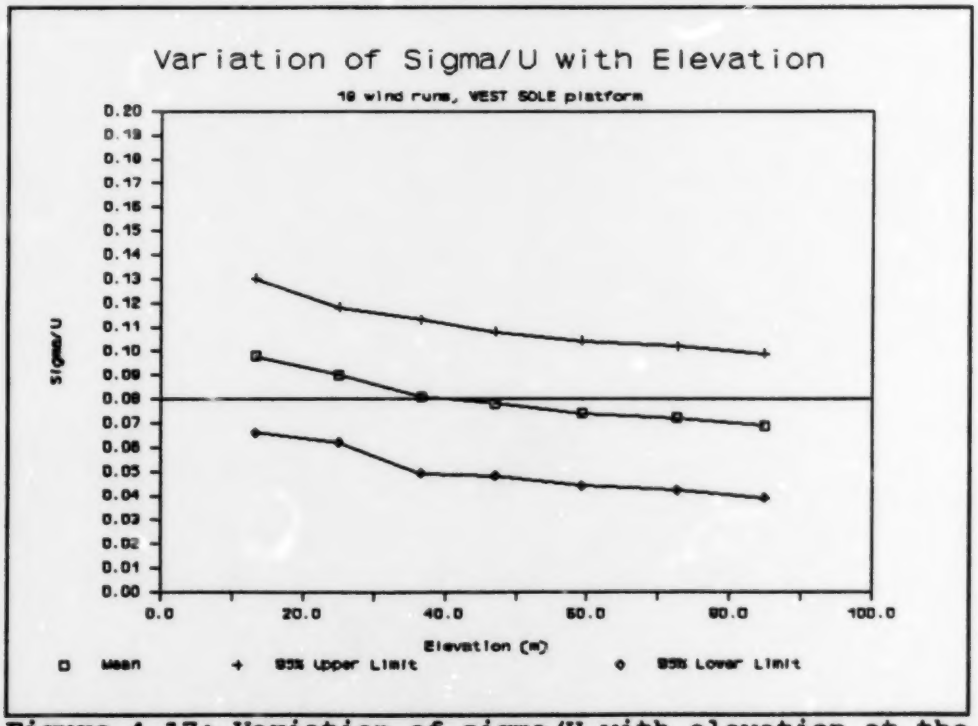


Figure 4.17: Variation of sigma/U with elevation at the WEST SOLE platform.

u_* which increased with elevation, in violation of theory. It was not possible to include stability effects directly into the calculation of u_* because of uncertainties in the air and sea temperature data. However, an attempt was made to estimate stability corrected values of u_* by fitting the Walmsley (1988) over-water wind profile model to the observed wind data. Two reasonable quality profiles were identified as being representative of stable and near-neutral conditions. These were the first hourly profile of run 5_3 (stable) and the first hourly profile of run 29_1 (near-neutral). The Walmsley (1988) profile model was fitted to the observed profiles by adjusting the sea-surface temperature (the sea-surface temperatures supplied by Wills were 5-day climatological averages). The computed values for u_* (now incorporating stability effects) were then used to investigate the stability dependence of σ/u_*.

Figures 4.18 and 4.19 compare profiles of σ/u_* with and without stability correction for the stable and near-neutral cases. The impact of the stability correction to u_* is readily apparent in the stable case. Linear regression analysis showed that the slope of the uncorrected profile (-0.01321) was significantly higher (95% level) than the neutral case (-0.00856). In contrast, the slope of the corrected stable case (-0.00814) was not significantly different from the neutral condition, and the correction produced σ/u_* values which agreed well with the observed neutral results. The above results suggest stability has a negligible impact on σ/u_* provided u_* has been corrected for atmospheric stability. It is also readily apparent that the assumption of a neutral boundary layer in gust models such as Forristall (1987) could lead to sizeable errors in estimated gust factors. Taking the above stable case as an example, if we assume that σ/u_* can be estimated by

$$\sigma = 2.26\ u_* \qquad (35),$$

the following results are obtained for 0.2 sec gust factors at 13.4 and 84.9 m elevations:

Table 4.4

Estimated gust factors following Forristall (1987) showing effect of stability correction to u_*.

z (m)	Obs. G(0.2,3600)	Pred. G(0.2,3600)	
		Corrected u_*	Neutral u_*
13.4	1.32	1.27	1.29
84.9	1.17	1.19	1.26

These results show that for this stable profile, the neutral assumption predicted gust factors which exhibited little height variation, and which overpredicted gust factors at higher elevations. In unstable cases, the converse would be true i.e. 'neutral assumption' gust factors would decrease rapidly with height underestimating gust factors at higher elevations. The latter error is of more concern for the design of structures off the east coast of Canada where unstable conditions are frequently experienced in winter storms.

5.0 EVALUATION OF OVER-WATER GUST PREDICTION METHODS:

There are a number of techniques available for predicting gust factors offshore. These include McClintock et al. (1987), Forristall (1987) and Mackey (1970) (cited in Dello Stritto et al., 1985). An evaluation was carried out of these techniques

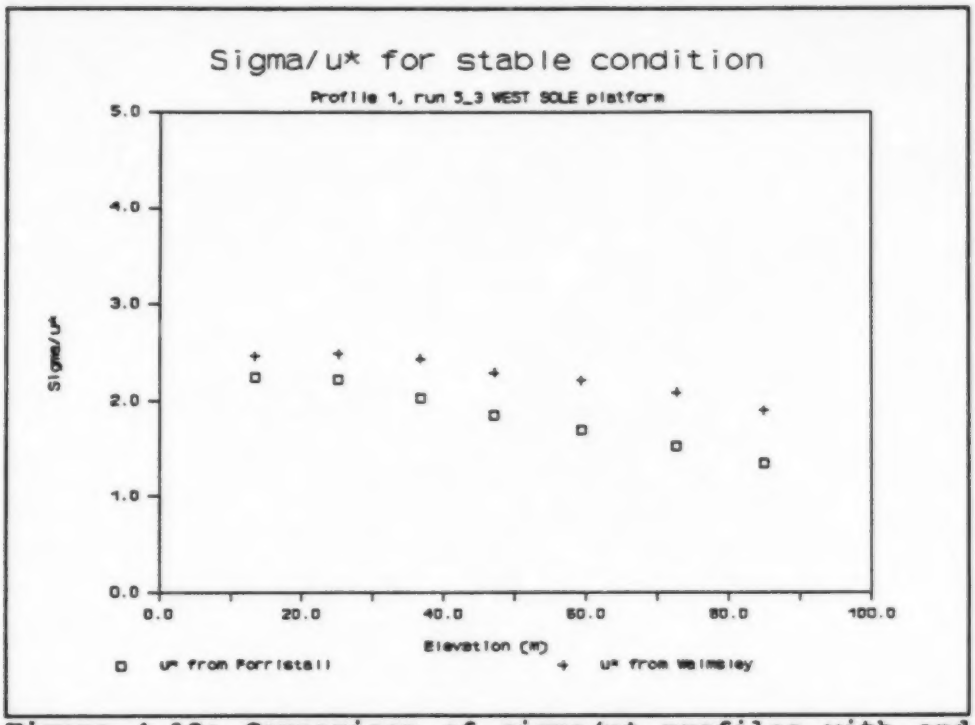


Figure 4.18: Comparison of sigma/u* profiles with and without stability correction for stable conditions at the WEST SOLE platform.

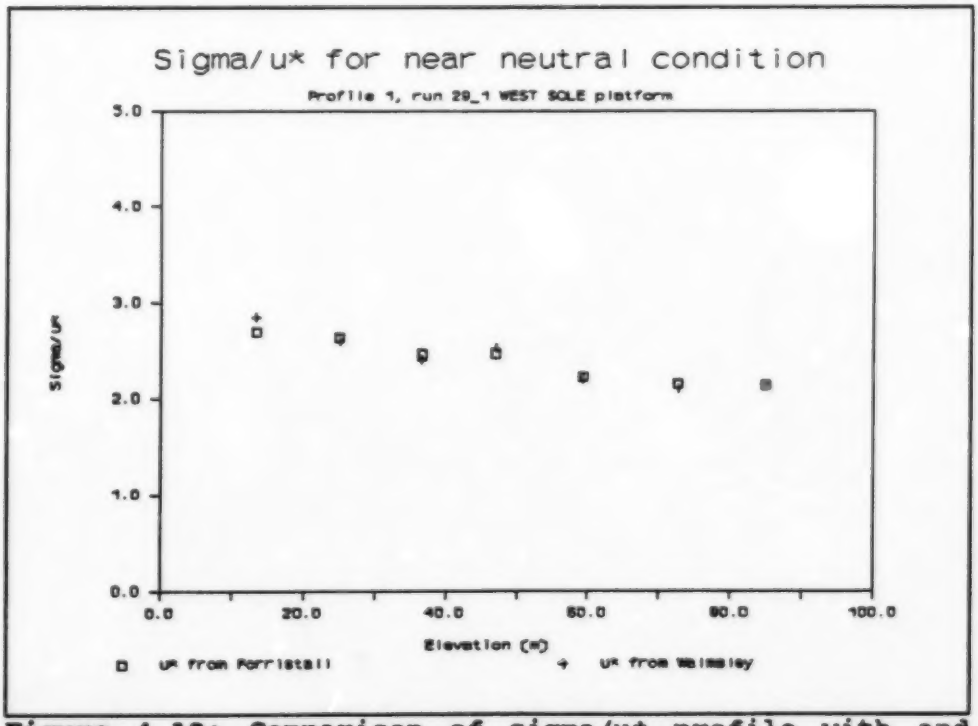


Figure 4.19: Comparison of sigma/u* profile with and without stability correction for near-neutral conditions at the WEST SOLE platform.

with mean gust factors from the three offshore locations, and for individual gust factors. In addition to these approaches, variations on Forristall and McClintock were included in the evaluation. In all models, u_* was computed from Forristall's (1987) iterative procedure which assumes a neutral boundary layer with z_0 computed from equation (6). An advantage of this approach is that u_* can be computed from a given wind speed at any elevation in the boundary layer. A description of the Forristall (FOR) and McClintock (MCC) models has previously been given in Sections 2.1 and 2.2. Other models included in the evaluation are described below:

The Mackey (1970) Formula:

The Mackey formula (MAC) includes gust variation with elevation, gust duration and measuring interval. The formula is given in Dello Stritto et al. (1985) as

$$G(t,T) = 1.0 - 0.62\ [\ln(t/T)/(\ln(z/z_0))^{1.27}] \qquad (36).$$

The roughness length, z_0, was obtained from equation (6) with u_* estimated from the iterative technique employed by Forristall (1987).

Modified Forristall methods:

As wave height information is often not available, two variations of the Forristall method were investigated which excluded his wave factor. The first (MF1), used equation (33) to estimate σ as a function of u_* and elevation, while the second (MF2) used the constant relationship $\sigma/u_* = 2.26$.

Modified McClintock et al. method:

As equation (21) incorporates no variation from increasing wind speed, gust duration or elevation, it yields a single gust factor making evaluation somewhat difficult. To get around this problem, the method was modified (MMC) by making σ_{Gi} a variable. This was achieved by replacing the constant -0.0208 in equation (21) with

$$-2.0\ (\sigma/U)^2 \qquad (37),$$

where σ was estimated from equation (33).

5.1 Mean gust factor comparison:

The mean gust factor comparison was split into two parts to investigate model performance for (1) changing gust duration and measuring interval, and (2) elevation. In the first case, average gust factors from the BEDFORD TOWER were used. These were the best quality, independent data available (models MF1, MF2, and MMC were all based on WEST SOLE data). Wave height data were not available for this comparison[2] so the Forristall (1987) model was run with an assumed H_s value of 3.0 m. The mean wind speed over all wind runs at the BEDFORD TOWER was 18.2 m/s. Model results for gust durations of 0.2, 1 and 3 sec and measuring intervals of 600, 1200 and 2400 sec are presented in Table 5.1 (evaluation of 15 and 60 sec gusts was not possible because the approximation used in the Forristall method was no longer valid). The rms error and Willmott index of agreement, d, were used as indices of model performance. The d-index is preferred over r^2 for model comparisons because it measures accuracy rather than degree of linear association. d is defined by (Willmott, 1982):

[2] Wave spectra and rms wave height data are available from the Bedford Institute of Oceanography.

Table 5.1

Comparison of computed gust factors with mean gust factors observed at BEDFORD TOWER, z = 13.4 m.

t (sec)	T (sec)	Obs. G(t,T)	Predicted G(t,T) FOR	MF1	MF2	MAC	MCC	MMC
0.2	600	1.30	1.32	1.32	1.29	1.28	-	-
1.0	600	1.26	1.28	1.28	1.25	1.22	1.34	1.34
3.0	600	1.23	1.24	1.24	1.22	1.18	-	-
0.2	1200	1.33	1.34	1.34	1.31	1.30	-	-
1.0	1200	1.29	1.30	1.30	1.27	1.25	1.36	1.36
3.0	1200	1.25	1.26	1.26	1.24	1.21	-	-
0.2	2400	1.35	1.35	1.36	1.32	1.33	-	-
1.0	2400	1.31	1.31	1.32	1.29	1.27	1.38	1.38
3.0	2400	1.28	1.28	1.28	1.26	1.23	-	-
RMSE			.012	.013	.018	.038	.073	.073
Willmott d-index			.973	.971	.933	.820	-	-

Table 5.2

Comparison of computed gust factors with mean 1 sec gust factors observed at three offshore locations.

z (m)	U (m/s)	T (sec)	Obs. G(1,T)	Predicted G(1,T) FOR	MF1	MF2	MAC	MCC	MMC
13.4	14.1	3600	1.34	1.38	1.31	1.28	1.26	1.39	1.37
25.1	15.3	3600	1.31	1.35	1.28	1.26	1.24	1.39	1.34
36.7	16.0	3600	1.27	1.34	1.26	1.26	1.23	1.39	1.32
47.1	17.2	3600	1.26	1.32	1.25	1.25	1.23	1.39	1.30
59.3	17.7	3600	1.23	1.31	1.24	1.25	1.23	1.39	1.29
72.7	17.9	3600	1.23	1.31	1.23	1.24	1.22	1.39	1.27
84.9	18.3	3600	1.22	1.30	1.21	1.24	1.22	1.39	1.26
13.4	18.2	2400	1.31	1.31	1.32	1.29	1.27	1.38	1.38
82.6	18.0	1200	1.24	1.33	1.20	1.22	1.19	1.36	1.24
RMSE				.066	.021	.030	.045	.125	.044
Willmott d-index				.581	.930	.760	.607	.352	.789

$$d = 1 - [\Sigma(P_i - O_i)^2/\Sigma(|P'_i| + |O'_i|)^2],\ 0 \leq d \leq 1 \qquad (38),$$

where O_i = observed gust
P_i = corresponding predicted gust
$P'_i = P_i - \bar{O}$
$O'_i = O_i - \bar{O}$.

The height comparison was carried out with average 1 sec gust factors from all three locations. The WEST SOLE data dominate this comparison which is unfortunate since two of the models, MF1 and MMC, incorporated expressions derived from the WEST SOLE wind data which related σ/u_* to elevation. It was therefore anticipated *a priori* that these two models were likely to perform better. The results of this comparison are shown in Table 5.2. H_s was assumed to be 3.0 m for the WEST SOLE and BEDFORD TOWER cases, while an average value of 4.21 m was obtained from BOW DRILL 3 wave reports. The average wind speed values used in the gust models are shown in Table 5.2.

Both the Forristall-based models and the Mackey formula performed quite well at replicating observed gust factor variation with gust duration and measuring interval. The McClintock models overpredicted gust factors but provided a realistic response to changing measuring interval. FOR and MAC however, were not as good at replicating gust factor variation with elevation because they assumed neutral conditions where wind runs from the WEST SOLE platform were more frequently stable (see Section 4.3.3). The relationship expressed in equation (33) corrected for this effect, thus MF1 and MMC exhibit similar height changes in gust factors to those observed. However, these two models are likely to have limited applicability since they are based on a site-specific empirical correction factor. In light of this, while MF1 was the best overall model at predicting mean gust factors, MF2 is probably the better general approach to use, particularly if stability effects are included in the computation of u_*. The MCC and MMC models overpredicted mean gust factors, suggesting that the normal distribution may not be suitable for estimating gust factors in the tail of the distribution. MCC is clearly unsuitable for offshore applications in its current form since it is insensitive to variation in wind speed, elevation, stability and gust duration.

5.2 Individual gust factor comparison:

In addition to the above comparison of mean gust factors, an evaluation was carried out of the FOR, MAC and MF2 models for individual gust factors observed at the BOW DRILL 3 and BEDFORD TOWER. In the case of the BOW DRILL 3, observed significant wave height values were incorporated into the FOR model. Results of FOR and MF2 models with the BOW DRILL 3 data are shown in Figures 5.1 and 5.2 while the performance of the MAC and MF2 models with the BEDFORD TOWER data are shown in Figures 5.3 and 5.4.

The FOR model clearly overpredicted gust factors at the BOW DRILL 3, although if the outliers are ignored, there is evidence that the model is able to account for some of the variation in observed gust factors. There are a number of reasons which may have contributed to the poor performance of the FOR model at this site compared to the good performance shown by Forristall (1987) for Gulf of Mexico hurricanes. First and most importantly, the wave factor computation and relationship to σ/u_* used in FOR (equations 15 and 16) are largely based on Gulf of Mexico hurricanes which can have quite different wind/wave conditions than east coast extratropical cyclones. Secondly, as outlined previously, there was a poor correlation between gust factors and wave height at the BOW DRILL 3 which may be related to anemometer height and/or flow distortion effects.

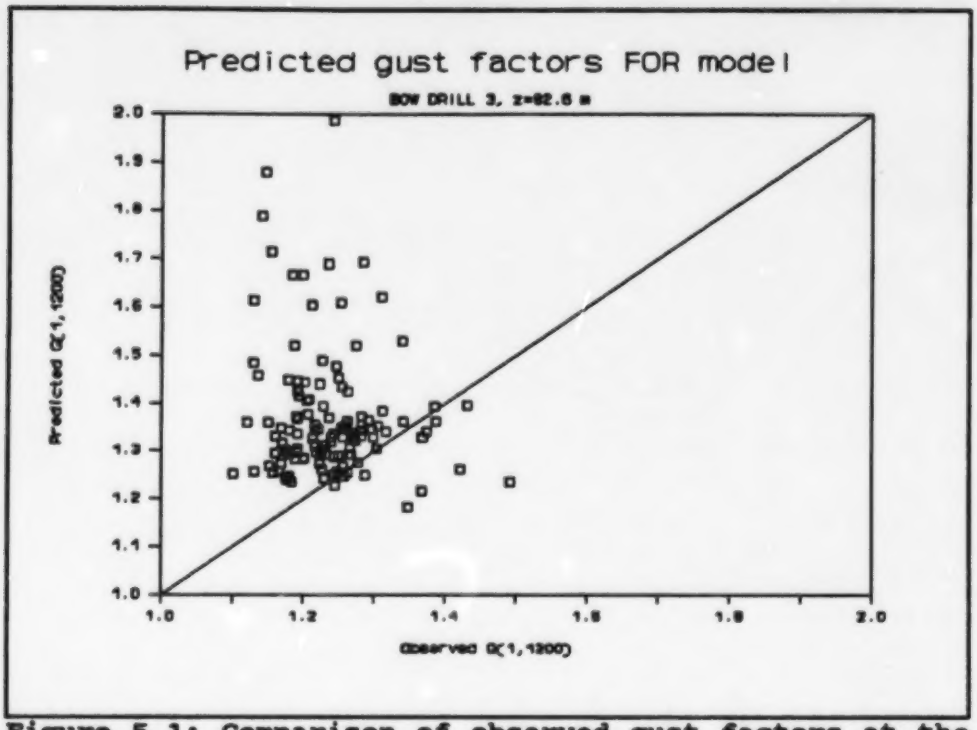


Figure 5.1: Comparison of observed gust factors at the BOW DRILL 3 with predicted gusts from the FOR model.

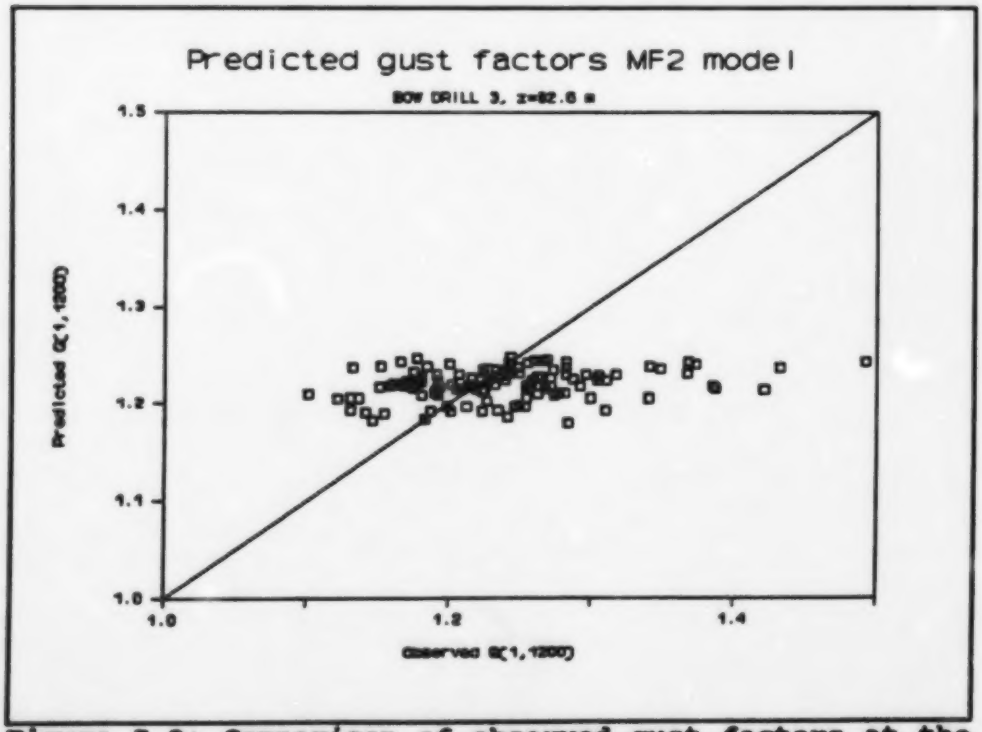


Figure 5.2: Comparison of observed gust factors at the BOW DRILL 3 with predicted gusts from the MF2 model.

The FOR results contrast with MF2 where the model is unable to replicate observed gust factor variation. The same response is evident in Figures 5.3 and 5.4 for MF2 and MAC. Here the observed and predicted means are more or less coincident, but the models are clearly unable to account for variation in individual gust factors.

5.3 Recommendations for computing offshore gust factors:

There are two ways to approach the above-noted inability of general gust factor models at replicating observed variation in offshore gust factors:

(1) Apply a confidence interval to the predicted gust factor values based on observed gust factor variability;

(2) Develop a more theoretical gust model incorporating stability effects and recent theory on the relationship between surface wave parameters and over-water turbulence.

The BEDFORD TOWER gust factor results showed that where wind speed data were low-pass filtered and the trend removed, the standard deviation of gust factors with durations less than 15 seconds was largely insensitive to sample length and gust duration. Typical gust factor standard deviations were 0.05 at the BEDFORD TOWER (z = 13.4 m). WEST SOLE gust factors exhibited standard deviations twice this value for elevations below 30 m. However, this is likely due to the combined effects of flow distortion and not applying a low-pass filter or removing trend. Of the three data sets, the BOW DRILL 3 data are more representative of an open ocean environment and indicate a gust factor standard deviation of 0.07 at 82.6 m elevation. This latter value yields a 95% confidence limit of ±0.14 which can be applied to predicted mean over-water gust factors.

The above gust models contain a number a theoretical deficiencies, e.g. they do not take atmospheric stability into account, and the computation of u_* is based on Charnock's relation, which is considered inadequate for describing wind drag over water. It would therefore be appropriate to develop a gust model which includes stability effects and which incorporates Geernaert et al.'s (1987) new proposed relationship between drag coefficient and the ratio C_0/u_* (equation 8). The steps used to estimate gust factors from this new model are outlined below:

- estimate u_* from Walmsley (1988) including stability effects;
- estimate C_{DN} based on wave age (equations 7 and 8);
- compute new u_* based on C_{DN} computed above, and U_{10} from the Walmsley model wind profile;
- estimate σ from equation (35);
- compute gust factors from a universal over-water spectrum following Forristall (1987).

The above model was run on the BOW DRILL 3 gust data set obtained at z = 82.6 m above sea level, with typical mean wind speeds in the range of 15-30 m/s. The model results (Fig. 5.5) revealed little improvement in predicting individual gust factors, firstly because stability effects were relatively small, and secondly, because it was found that C_0 did not have an appreciable influence on C_{DN}. Figure 5.6 compares C_{DN} values as a function of wave age from the Geernaert et al. (1987) relationship and C_{DN} values obtained from the Walmsley (1988) model which parameterized surface roughness effects through Charnock's z_0 relation following

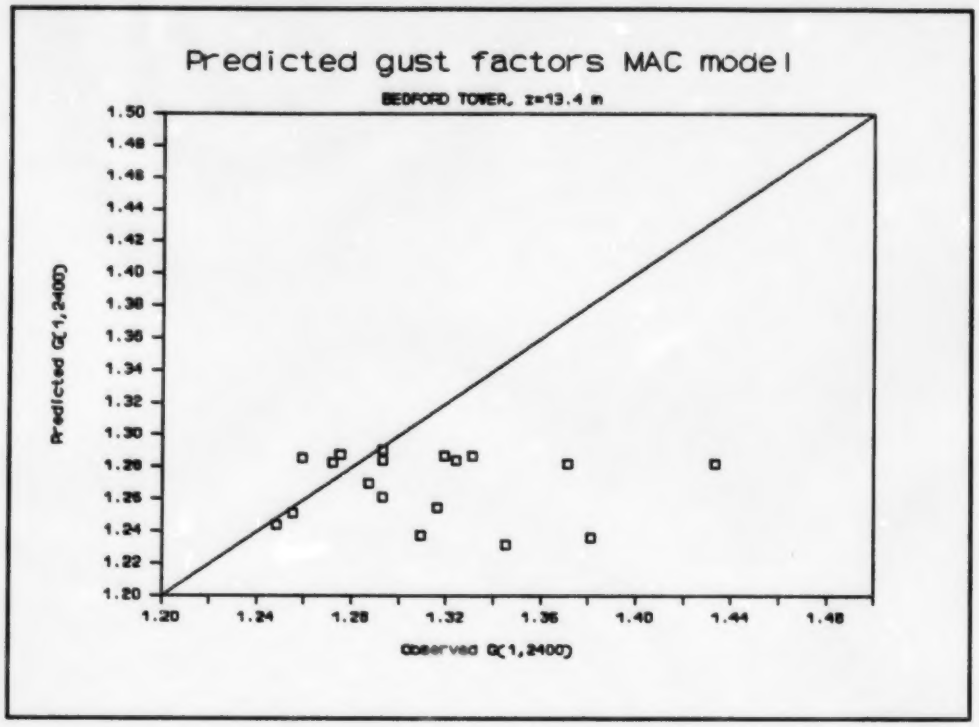


Figure 5.3: Comparison of observed gust factors at the BEDFORD TOWER with predicted gusts from the MAC model.

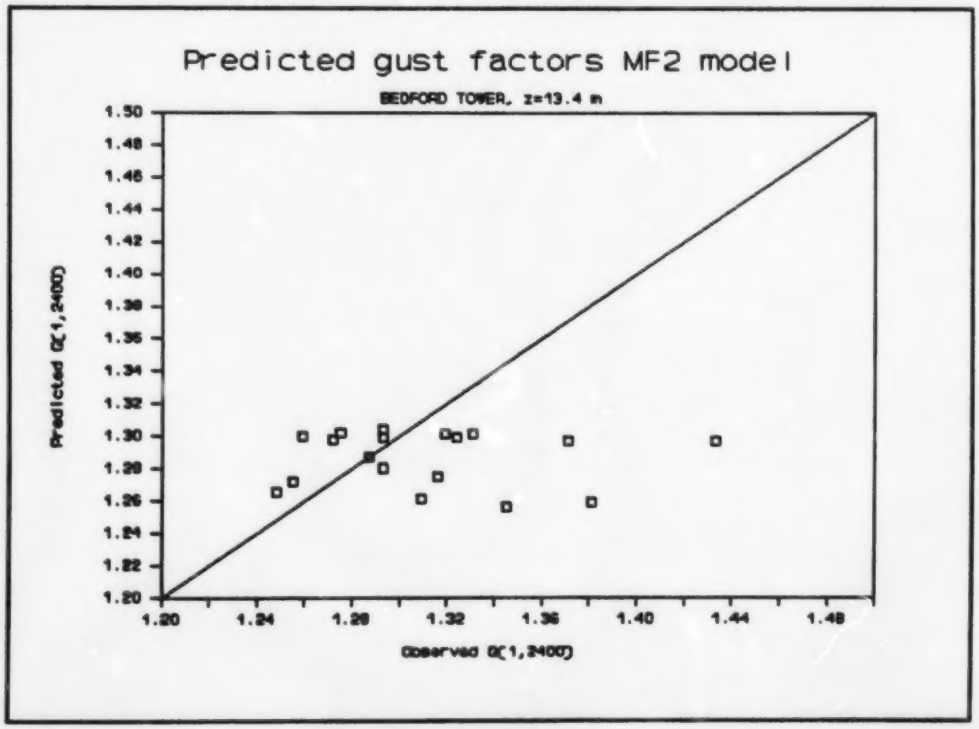


Figure 5.4: Comparison of observed gust factors at the BEDFORD TOWER with predicted gusts from the MF2 model.

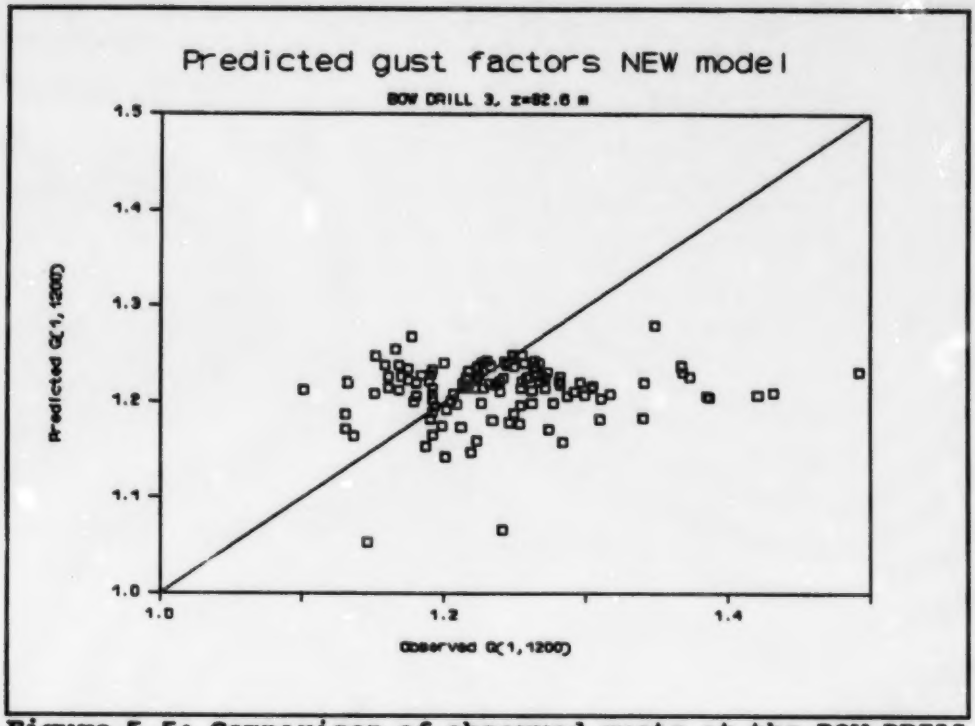


Figure 5.5: Comparison of observed gusts at the BOW DRILL 3, z=82.6 m, with gust predicted by the NEW gust model incorporating stability and wave age.

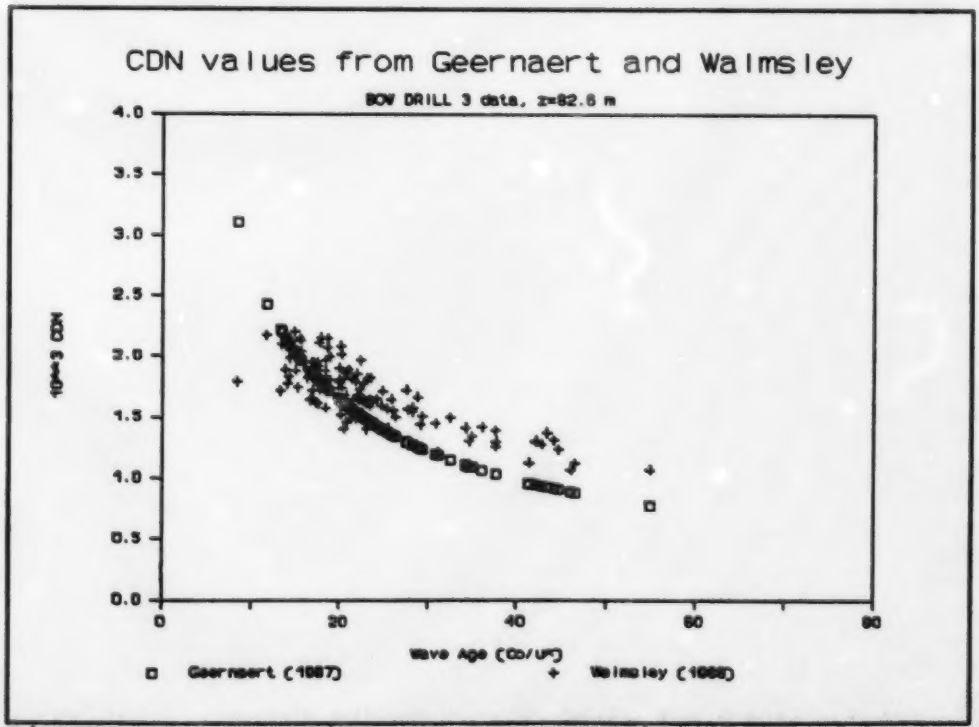


Figure 5.6: Comparison of drag coefficients used by the Walmsley (1988) boundary-layer model with those based on wave age following Geernaert et al. (1987).

Smith (1981). Specifying C_{DN} as a function of wind speed made little difference to the results shown in Figure 5.5.

If gust factors are plotted against wave age (Fig. 5.7), the results show less dependence than was previously observed for wind speed and significant wave height. However, the results are strikingly similar to Figure 5.8 where gust factors are plotted against Forristall's wave factor. Wave age and wave factor were subsequently compared (Fig. 5.9) revealing a surprisingly close relationship (approximated by $w = (C_0/u_*)/20$) given the empirical basis of the wave factor. Thus, we find that Forristall (1987) is essentially using wave age in his estimate for σ, i.e. for this particular dataset, equation (16) can be expressed as

$$\sigma/u_* = 0.15\ C_0/u_* \qquad (39).$$

Turbulence intensity is now directly related to wave age rather than indirectly through the drag coefficient and u_*. The only problem with equation (39) is that Geernaert et al. (1987) found no clear evidence of any relationship between σ/u_* and wave age.

The above modelling approach and the relationship expressed in equation (39) need to be investigated further with a higher quality data set. The very low correlation between significant wave height and gust factors at the BOW DRILL 3 suggests that even though the anemometer was in the boundary layer at the wind speeds observed (15-30 m/s), sources of turbulence other than those generated by surface roughness may be influencing the data. The above method of incorporating wave age into a gust prediction model also contains some inconsistencies which may influence results, i.e. the computation of C_0 is dependent on a previously computed value of u_*, while the new computed value of u_* is more sensitive to the previously computed value of U_{10} than the new C_{DN}. It was beyond the scope of this investigation to develop a new marine boundary layer model which incorporated wave age in a more consistent fashion.

6.0 CONCLUSIONS

The main conclusions of this study can be summarized as follows:

Average gust factors:

Average gust factors computed at The WEST SOLE and BEDFORD TOWER sites at 13.4 m elevation showed good agreement. Typical values for G(1,3600) and G(3,3600) were 1.34 and 1.30 respectively, in general agreement with values published by DnV (1977) and Smith and Chandler (1987). The height variation of average gust factors from the WEST SOLE site was observed to closely approximate a power law with a negative exponent. The magnitude of the exponent varied as a function of gust duration, with values of -0.054 and -0.047 for G(1,3600) and G(3,3600) respectively. Power laws also provided good approximations for variation of mean gust factors with gust duration, t, and measuring interval, T.

Gust factor sensitivity:

In terms of their sensitivity, computed gust factors were found to be most sensitive to variation in gust duration ($t < 15$ sec), followed by elevation and measuring interval. Increasing wind speed was observed to have a slight effect of increasing gust factors, but the amount of variance explained was typically low, in agreement with the results of Vickery et al. (1985) and Smith and Chandler (1987). The investigation of gust factor sensitivity to atmospheric stability was hampered at

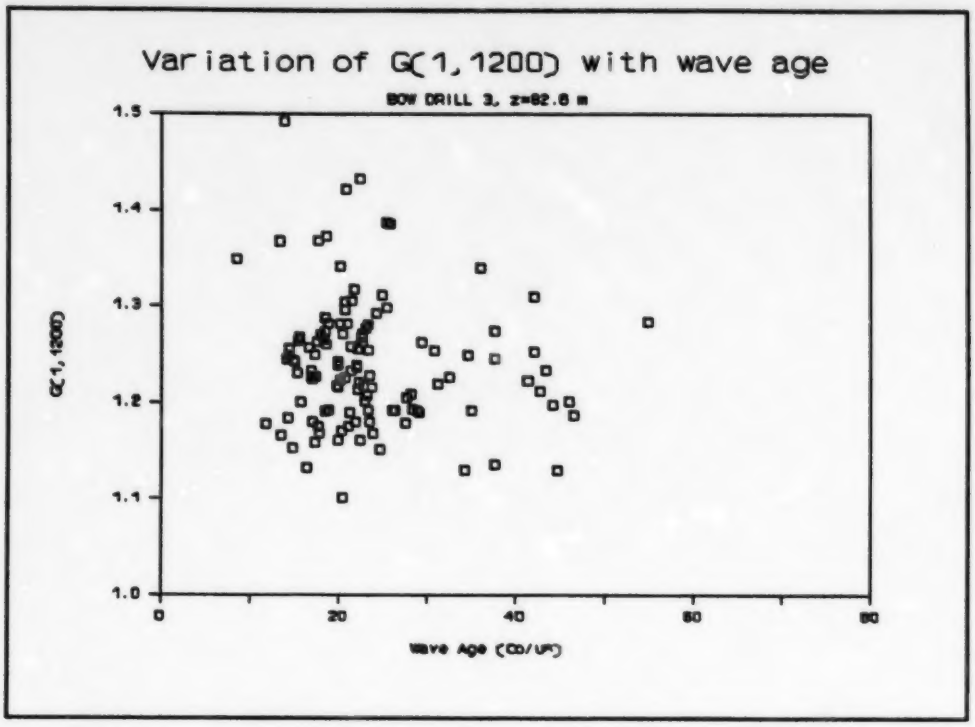


Figure 5.7: Comparison of gust factors observed at the BOW DRILL 3, z=82.6 m, with wave age.

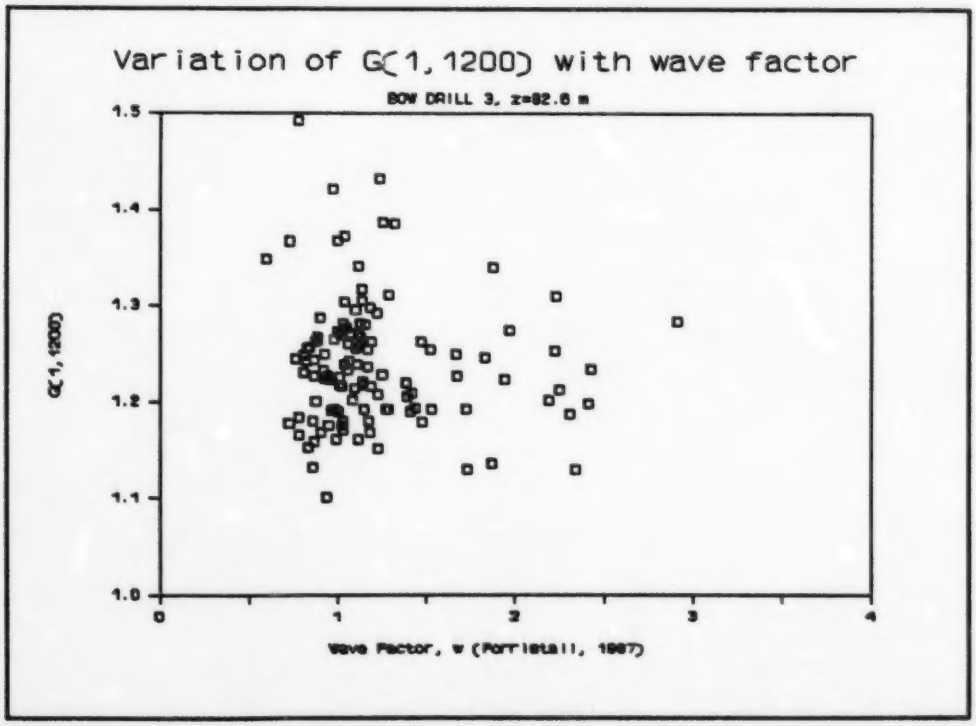


Figure 5.8: Comparison of gusts observed at the BOW DRILL 3, z=82.6 m, with Forristall's (1987) wave factor.

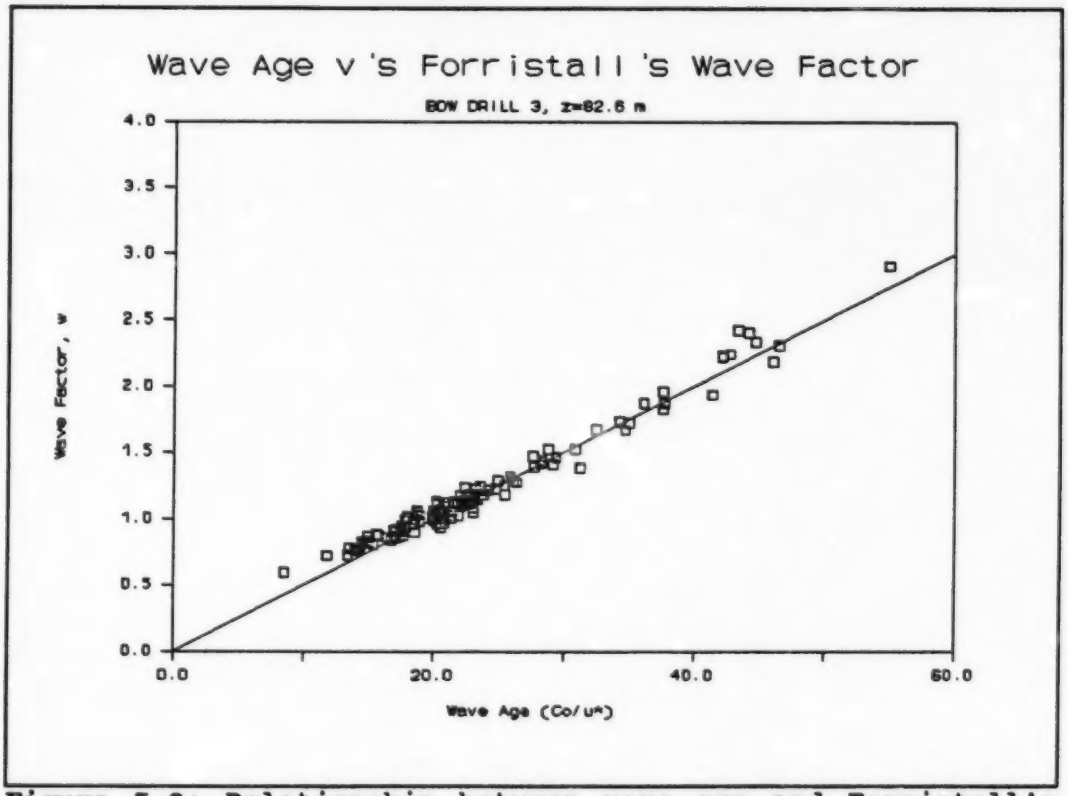


Figure 5.9: Relationship between wave age and Forristall's wave factor for the BOW DRILL 3 data. The line shown is w = (Co/u*)/20.

the WEST SOLE site by poor quality temperature data. The results suggested only a slight dependence on stability at lower elevations, (gustiness decreasing with increasing stability) in general agreement with Smith and Chandler (1987). Atmospheric stability was, however, found to be important for the prediction of gust profiles. The BOW DRILL 3 gust factors showed little sensitivity to variation in significant wave height, in contrast to Vickery et al. (1985) who found higher gust factor/Hs correlations than for wind speed. The reasons for this difference were not clear.

The above discussion suggests the following sensitivity ranking for over-water gust factors:

1. Gust duration (t < 15 sec)
2. Elevation (10-100 m)
3. Measuring interval (600-3600 sec)
4. Wave height
5. Wind speed
6. Atmospheric stability

Turbulence intensity:

Mean values of 2.26 and 2.58 were found for σ/u_* at the WEST SOLE and BEDFORD TOWER sites. These are in general agreement with published over-water values of σ/u_* which are typically in the order of 2.5. Mean values of σ/U were 0.080 and 0.106 for the respective sites. σ/u_* was observed to exhibit less wind speed dependence than σ/U at both sites in agreement with Geernaert et al. (1987) and Forristall (1987). σ/u_* also displayed less sensitivity to changes in elevation than σ/U. These findings suggest that σ/u_* is a more stable parameter to use in gust factor models than σ/U.

Mean σ/u_* results from WEST SOLE were observed to decrease linearly with height. However, it was noted that this dependence was accentuated by not taking stability effects into account when computing u_*, and from flow distortion at lower levels. When confidence levels were considered, it was found that this relationship was not significantly different from $\sigma/u_* = 2.26$. The same conclusion was reached for $\sigma/U = 0.080$. The inclusion of stability in the calculation of u_* was found to decrease the height dependence of σ/u_*, and reduce variability in computed values of σ/u_*. Inclusion of stability effects in the calculation of u_* was also found to be important for reliable prediction of gust factors at higher elevations from gust models which estimate σ from u_* following Forristall (1987). This is particularly important in unstable conditions where use of a neutral assumption in the computation of u_* would cause the above gust models to underpredict gust factors at higher elevations.

Gust factor models:

The main conclusions of the gust factor model investigation were:

Statistical theory can predict the variation of average gust factors with wind speed, gust duration, measuring interval and elevation;

There is a large remaining variability which cannot be predicted with present models.

The MF2 model was considered the best general approach for computing mean gust factors as functions of gust duration, wind speed and elevation. However, as noted earlier, stability effects must be included for reliable prediction of gust factors at higher elevations. The McClintock et al. (1987) model is not recommended as it is

unable to take into account variation in gust duration, elevation or wind speed. Even where this model was modified to incorporate these effects, it was found to consistently overpredict. This overprediction suggests that the normal distribution used by this model may not be adequate for representing extreme gusts.

No models were able to successfully account for the observed variability in individual gust factors. Forristall (1987) was the only model which showed some indication of reproducing gust variability at the BOW DRILL 3 site. However, the results exhibited a large degree of scatter and contained a number of large overpredictions. Comparison of Forristall's wave factor and wave age for the BOW DRILL 3 data revealed a close relationship which suggested the Forristall model was actually using wave age to estimate σ. However, the role of wave age in over-water turbulence has not been clearly demonstrated to date. Inclusion of stability effects and Geernaert et al.'s (1987) drag coefficient/wave age relationship into the MF2 model did little to improve individual gust prediction. It was concluded that data quality was probably a contributing factor in the poor model response at the BOW DRILL 3 site, and that the models should be re-evaluated with a higher quality wind/wave data set.

Recommendations for further work:

The main problems encountered in this study were related to data quality. These included flow distortion effects, unreliable air and sea temperatures, and missing important information such as significant wave heights. Without a higher quality, complete data set, further analysis of gust factors and models is unwarranted. Therefore, the main recommendation of this study is to obtain a more detailed over-water wind data set to investigate turbulence relationships in the marine boundary layer with more confidence. A suitable dataset would need to meet the following requirements:

- data collection platform located in an open ocean environment;
- continuous wind speed measurements at several elevations in the boundary layer (10-50 mASL) over long periods, with a sampling frequency of at least 5 Hz;
- continuous measurements of sea-surface displacement at the wind measurement site;
- continuous air-sea temperature difference measurements;
- detailed documentation of flow distortion effects following Vickery et al. (1985).

The main aim of further analysis with such a data set would be to obtain a greater understanding of the mechanisms responsible for variation in individual gusts over water. In particular, the role of sea-surface displacement variation on turbulence. The good performance of the Forristall (1987) gust model in hurricanes indicates that there is some theoretical basis for the 'wave factor' correction used by Forristall. The remaining challenge is to articulate this theory to develop a general gust factor model applicable to all offshore environments.

7.0 REFERENCES

Agnew, T.A. and V.R. Swail, 1985: Proceedings International Workshop on Offshore Winds and Icing. Halifax, Nova Scotia, October 7-11, 1985, 407 pp.

CERC, 1977: Shore protection manual. Volume I. U.S. Army Coastal Engineering Research Centre, Washington, D.C.

Charnock, H., 1955: Wind stress on a water surface. *Q.J.R. Meteorol. Soc.* 81: 639-640.

Dello Stritto, F.J., J.R. Benoit and J.A.N. Ransom, 1985: Wind-related needs of offshore industry: a select review. In Proceedings of International Workshop on Offshore Winds and Icing, T.A. Agnew and V.R. Swail (eds.), Halifax, Nova Scotia, October 7-11, 1985, pp. 196-213.

Det norske Veritas, 1977: Rules for the design, construction and inspection of offshore structures - Appendix A, Environmental Conditions.

Fordham, E.J., 1985: The spatial structure of turbulence in the atmospheric boundary layer. *Wind Engineering* 9(2): 95-133.

Forristall, G.Z., 1987: Wind spectra and gust factors over water. Proceedings 20th Annual OTC, Houston, Texas, May 2-5, 1988, OTC 5735, pp. 449-460.

Garrat, J.R., 1977: Review of drag coefficients over oceans and continents. *Mon. Weather. Rev.* 105: 915-929.

Geernaert, G.L., 1987: On the importance of the drag coefficient in air-sea interactions. *Dynamics of Atmospheres and Oceans* 11: 19-38.

Geernaert, G.L., S.E. Larsen and F. Hansen, 1987: Measurements of wind stress, heat flux and turbulence intensity during storm conditions over the North Sea. J. Geophys. Res. 92(C12): 13,127-13,139.

Large, W.G., 1979: The turbulent fluxes of momentum and sensible heat over the open sea during moderate to strong winds. Ph.D. Thesis, Inst. Oceanogr. and Dept. Physics, University of British Columbia, 180 pp.

Marquardt, D.W., 1963: An algorithm for least squares estimation of nonlinear parameters. *J. Soc. Ind. Appl. Math.* 2: 431-441.

McClintock, J.D., G.S. Pond and L.W. Davidson, 1987: Offshore wind gust climatologies. Canadian Climate Centre Report No. 87-16, Atmospheric Environment Service. Downsview, Ont., 84 pp.

Roll, H.U., 1965: *Physics of the marine atmosphere*. Academic Press, New York, 426 pp.

Smith, S.D., 1980: Wind stress and heat flux over the ocean in gale force winds. *J. Phys. Oceanogr.* 10: 709-726.

Smith, S.D., 1981: Factors for adjustment of wind speed over water to a 10-metre height. Report BI-R-81-3, Bedford Inst. Oceanogr., Dartmouth, N.S., 29 pp.

Smith, S.D. and P.C.P. Chandler, 1987: Spectra and gust factors for gale force marine winds. *Boundary-Layer Meteorol.* 40: 393-406.

Vickery, P.J., B.J. Vickery and A.C. Davenport, 1985: Gust factors and turbulence measured at 50 m over the sea off Sable Island. In Proceedings of International Workshop on Offshore Winds and Icing, T.A. Agnew and V.R. Swail (eds.), Halifax, Nova Scotia, October 7-11, 1985, pp. 196-213.

Walmsley, J.L., 1988: On theoretical wind speed and temperature profiles over sea with applications to data from Sable Island, Nova Scotia. *Atmosphere-Ocean*, 26(2): 203-233.

Willmott, C.J., 1982: Some comments on the evaluation of model performance. *Bull. Amer. Meteorol. Soc.* 63(11): 1309-1313.

Wills, J.A.B., 1982: Report on the West Sole wind structure project 1982. National Maritime Institute Report R145, 59 pp.

Wills, J.A.B., 1986: Report on the West Sole wind structure project 1986. British Maritime Technology Commercial Report, 54 pp.

Wills, J.A.B., A. Grant and C.F. Boyack, 1986: The offshore mean wind profile. Offshore Technology Report OTH 86 286, British Maritime Technology, 36 pp.

APPENDIX A: Gust analysis summary tables.

Table A-1

Summary of 3 sec gust factors.

	WEST SOLE (13.4 m)			BEDFORD TOWER (13.4 m)		
(t,T)	n	G(t,T)	sd	n	G(t,T)	sd
(3,600)	204	1.21	0.087	77	1.23	0.048
(3,1200)	102	1.24	0.100	38	1.25	0.049
(3,2400)	51	1.28	0.126	18	1.28	0.053
(3,3600)	34	1.30	0.133	-	-	-

	WEST SOLE (84.9 m)			BOW DRILL 3 (82.6 m)		
(t,T)	n	G(t,T)	sd	n	G(t,T)	sd
(3,600)	204	1.13	0.041	248	1.18	0.057
(3,1200)	102	1.15	0.048	124	1.20	0.060
(3,2400)	51	1.17	0.055	-	-	-
(3,3600)	34	1.19	0.053	-	-	-

Table A-2

Summary of 15 sec gust factors.

	WEST SOLE (13.4 m)			BEDFORD TOWER (13.4 m)		
(t,T)	n	G(t,T)	sd	n	G(t,T)	sd
(15,600)	204	1.13	0.068	77	1.14	0.040
(15,1200)	102	1.16	0.081	38	1.16	0.044
(15,2400)	51	1.20	0.102	18	1.18	0.045
(15,3600)	34	1.22	0.122	-	-	-

	WEST SOLE (84.9 m)			BOW DRILL 3 (82.6 m)		
(t,T)	n	G(t,T)	sd	n	G(t,T)	sd
(15,600)	204	1.09	0.034	248	1.12	0.046
(15,1200)	102	1.11	0.043	124	1.15	0.049
(15,2400)	51	1.13	0.051	-	-	-
(15,3600)	34	1.15	0.046	-	-	-

Table A-3

Summary of 60 sec gust factors.

	WEST SOLE (13.4 m)			BEDFORD TOWER (13.4 m)		
(t,T)	n	G(t,T)	sd	n	G(t,T)	sd
(60,600)	204	1.07	0.051	77	1.08	0.031
(60,1200)	102	1.10	0.061	38	1.09	0.035
(60,2400)	51	1.13	0.084	18	1.11	0.038
(60,3600)	34	1.15	0.095	-	-	-

	WEST SOLE (84.9 m)			BOW DRILL 3 (82.6 m)		
(t,T)	n	G(t,T)	sd	n	G(t,T)	sd
(60,600)	204	1.05	0.027	248	1.08	0.038
(60,1200)	102	1.07	0.037	124	1.11	0.043
(60,2400)	51	1.10	0.045	-	-	-
(60,3600)	34	1.11	0.039	-	-	-

Table A-4

Summary of Richardson number calculations
for WEST SOLE wind data.

Run ID	Exposure	Ta_{85}	Ta_{25}	U_{85}	U_{25}	Ri
4_3	O	10.5	8.5	15.1	7.5	0.09
5_3	U	10.4	9.3	15.4	11.5	0.23
15_1	U	7.8	6.2	18.2	14.6	0.35
17_1_1	U	13.6	12.3	17.2	14.0	0.38
18_1_1	O	8.4	7.8	17.0	12.1*	0.10
19_1	O	11.0	10.1	17.1	12.4*	0.14
21_1_1	P	5.5	5.2	19.3	17.5*	0.58
21_2	O	5.2	4.7	32.6	24.1*	0.03
23_1	U	7.5	6.5	19.8	17.3	0.53
25_1	O	14.3	12.4	13.7	6.6	0.10
26_1_1	U	17.7	16.8	17.2	14.6	0.45
26_2	O	12.0	11.6	24.4	22.5*	0.56
27_1	U	10.7	9.9	20.0*	14.6	0.10
27_2	U	9.8	8.9	21.8	16.0	0.09
28_1	U	3.9	3.9	18.8	17.3	0.55
29_1	U	4.3	4.3	19.3	17.0	0.23
30_1	U	6.0	5.3	22.1	18.4	0.20
31_1	U	12.9	12.2	21.0	17.9	0.28
32_1	U	8.7	8.3	19.8	17.4	0.36
33_1	O	4.2	5.2	14.6	12.7*	-0.24
34_1	O	6.5	6.4	17.5	15.9	0.56

Exposure Codes: U-unobstructed; O-obstructed; P-partially obstructed
* Value interpolated or extrapolated

APPENDIX B: Wind profile comparison for Walmsley (1988) model.

The WEST SOLE wind speed profiles were generally unsuitable for model comparisons because of flow distortion effects and missing data. However, a good quality, smoothly-varying profile was found for the first hour of run 5_3. This was subsequently used to test the Walmsley (1988) wind profile model. The observed parameters used in the model were (wind and air temperatures from z=84.9 m):

T_{sea} = 9.0°C T_{air} = 10.4°C U = 16.0 m/s.

The result (Fig. B-1) showed that the observed profile was considerably more stable than predicted by the model. From communication with Wills of BMT, it was learned that the actual sea-surface temperature values experienced at the WEST SOLE site could differ significantly from the 5-day climatological averages supplied with the wind data. Decreasing sea-surface temperature 2.0°C produced the excellent results evident in Figure B-2. The best model results were obtained with data recorded from the highest elevation at 84.9 m, as these were least affected by flow distortion and sensor problems. The importance of including atmospheric stability in the estimation of vertical wind profiles can be clearly seen in the difference between the Walmsley (1988) model and a logarithmic profile which assumes a neutrally stratified boundary layer.

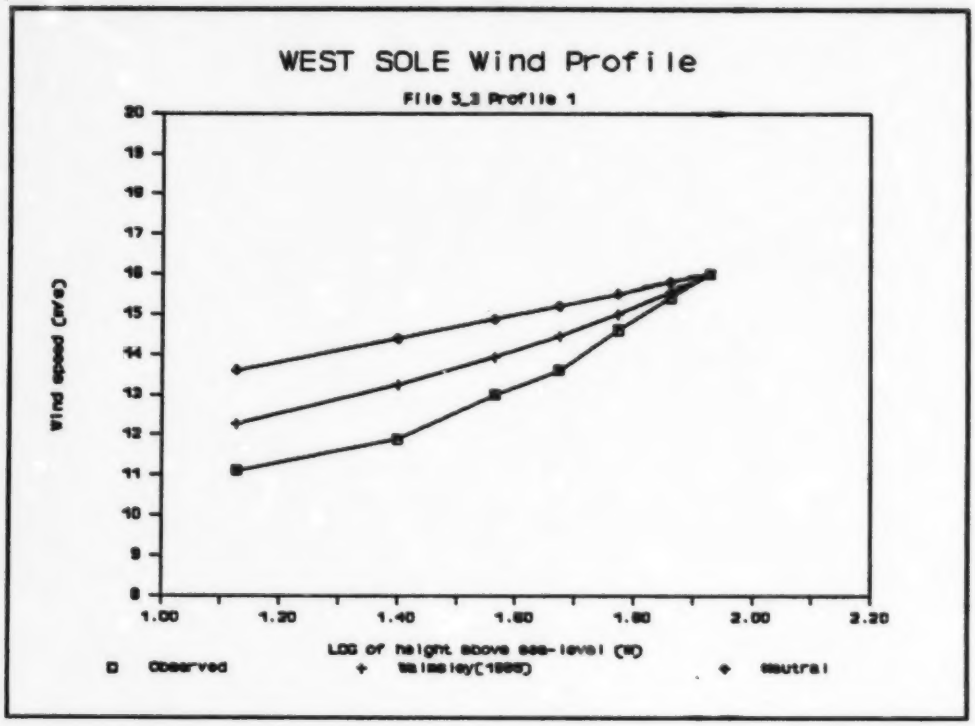


Figure B-1: Comparison of Walmsley (1988) wind profile model with climatological sea-surface temperature value.

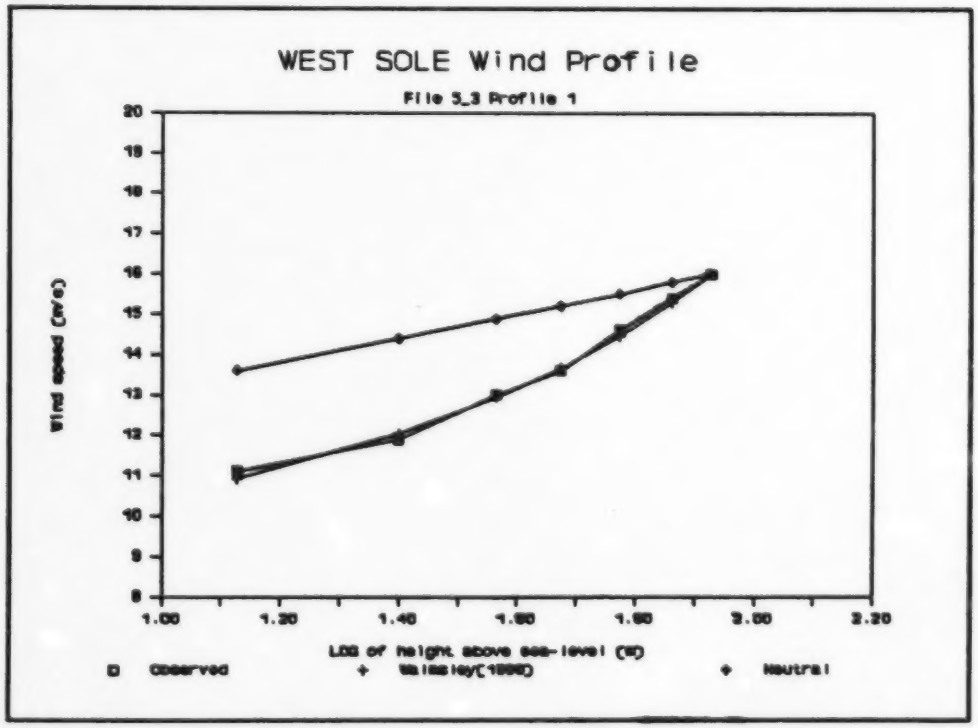


Figure B-2: Comparison of Walmsley (1988) wind profile model with a sea-surface temperature of 7.0 deg. C.